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THE APPRAISAL OF THREE GAS-FIRED SMALL-SCALE CHP SYSTEMS

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Abstract

The research in this thesis has undertaken a technical, economic and environmental appraisal of three gas-fired, small-scale Combined Heat-and-Power (CHP) systems together with a study of the UK's electricity supply industry (ESI) and CHP market. The purpose of each system is to attempt to utilise more of the heat and/or electricity output from the CHP unit. Within the non-technical research area, three scenarios for the evolution of the ESI have been developed to help establish how changes to forces acting within the industry, might affect the development of the UK CHP market. New applications of several strategic management analysis tools were used to develop and select the following scenarios: (i) New and reduced CO_2 limits set by the Climate Control Conference + stricter environmental legislation, (ii) Changes to the Pool mechanism for pricing electricity. (iii) Business as usual. It was concluded that in isolation scenarios 1 and 3 would aid the expansion of the CHP market, whereas scenario 2 is likely to hinder it. The selection of the scenarios and the implications for the ESI and CHP market are supported by the opinions of 'industry specialists', which were solicited in a survey specifically undertaken for this study.

The investigation into the first of the three technical systems involves the substitution of two separate CHP units in place of a single larger unit. The intention is to operate the larger of the two CHP units at maximum output to satisfy the base heat-load and to use the second unit for meeting peak loads. The results for five test-cases were produced via a newly-developed predictive model, and indicated that it is possible, for one of the case studies considered, to achieve shorter pay-back periods when using the double-unit - with a higher availability of 95% - rather than the single-unit system. In the other two cases (where CHP is a viable economic option), longer pay-back periods ensue by the installation of the two-unit rather than the single-unit system. The operation of the two-unit system can potentially increase energy-utilisation from the CHP units at one of the other sites. Furthermore, the proposed system can offer, in some cases, significant secondary benefits, which could encourage a potential investor in the technology. These benefits include the increased heat-and-electricity output, increased availability from the system, back-up from the secondary unit if one unit fails.

The second system determines the viability of an integrated small-scale CHP and TES system. Another predictive model was developed and tested on five test-cases. It was found that there is insufficient potential for the system and that the potential is limited by the following factors (i) CHP-sizing methodology, (ii) the relatively high capital cost for TES hardware and installation, (iii) the relatively low economic value attributed to heat and (iv) the availability of low-priced off-peak electricity. An industrial case study provided a rare and useful operational example of the proposed system and the findings indicated that the heat-store could reduce the

energy and monetary expenditures by up to 2.8% of the site's annual gas usage, displacing approximately 30 tones of CO_2 emissions each year. However, because of the high financial cost of the TES components and installation, the pay-back period produced would rarely be acceptable to a prospective investor, except in exceptional circumstances.

Finally, the viability of an integrated CHP/absorption chiller system was investigated. The effectiveness of these types of systems are dependent on several factors, namely: the source-water temperature from the hot-engine CHP unit - for a high COP - and the cooling load at the site, the cooling demand at the site and the temperature of the cooling water. A first-stage predictive model was developed to determine the initial appropriateness of the installation of the integrated system at a local hospital for the first time. The indications were that the cooling demand was too low and the surplus waste-heat from the CHP unit insufficient to make the system viable at the site. A second working-system was studied with a full CO_2 investigation undertaken. The intention was to compare the total CO_2 emissions for the integrated CHP and absorption chiller system with those for a similarly sized vapour-compression system. The results indicate that the installed system will produce 0.30kg CO_2/kWh_{coolth} compared with 0.27 kg and 0.32kg for two different types of vapour compression systems at design conditions. If the CHP heat output is increased - to supply all of the heat required by the absorption chiller - then the proposed system can displace up to 0.06 kg CO_2 per kWh_{coolth} at design conditions and 0.10 kg CO_2 per kWh of cooling delivered for lower cooling water temperatures. This represents a reduction of 22% and 40% respectively, when compared with the vapour-compressions system.

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IEA:	International Energy Agency.
IG:	Independent Generators.
IRR:	Internal Rate of Return.
JB:	Identified range of *Carrier* absorption-chillers.
LEB:	London Electricity Board.
LC:	Large Customers.
LiBr:	Lithium Bromide.
MEB:	Midlands Electricity Board.
MKGH:	Milton Keynes General Hospital.
MTC:	Millions of Tonnes of Carbon.
NGC:	National Grid Company.
NPV:	Net Present Value.
NFFL:	Non Fossil-Fuel Levy.
NFFO:	Non Fossil-Fuel Obligation.
OECD:	Organisation for Economic Co-operation and Development.
OFFER:	Office of Electricity Regulation.
OG:	Public electricity supply - Own Generation.
OFGAS:	Office of Gas Regulation.
ODP:	Ozone Depletion Potential.
p:	Pence.
P:	Pump Power, kW.
PCL:	Positive Concentration Limit.
PCM:	Phase-Change Material.
PD:	Power Density.
PF:	Power Factor.
PFI:	Private Finance Initiave.
PPP:	Pool Purchase Price.
PSP:	Pool Selling Price.
psi:	Pounds per square inch.
RECs:	Regional Electricity Suppliers.
SELCHP:	South East London Combined Heat-and-Power.
SMP:	System Marginal Price.
SRP:	Solution and Refrigerant Pumps.
S.T.E.E.P.:	Social, Technological, Economic, Environmental and Political.
SWALEB:	South Wales Electricity Board.
SWEB:	South West Electricity Board.
T & D:	Transmission and Distribution.
TES:	Thermal-Energy Storage.
TSC:	Theoretical Storage Capacity.
TSU:	Thermal-Storage Unit.
UCPTE:	The Union for the Coordination of Production and Transmission of Electricity.
UHC:	Unburnt Hydrocarbons.
UNIPEDE:	The International Union of Producers and Distributors of Electrical Energy.
VC:	Vapour Compression.

List of symbols

C_p:	Specific heat capacity (J $kg^{-1} K^{-1}$).
E_f:	Effect of each factor.
F_n:	Outcome factors.
GWh	Gigawatt hours (10^9W).
h:	Specific enthalpy , kJ $kg^{-1} K^{-1}$
km:	Kilometres.
kW_e:	Kilowatts electricity (10^3W).
kWh:	Kilowatt hour.
L_i:	Likelihood.
l:	Litre.
m:	Mass (kg).
mm:	Milli-metres.
MW_e:	Megawatts electricity (10^6W).
NO_x:	Nitrous oxides.
NO_x:	Oxides of nitrogen.
Pa:	Pressure, Pascals
PF_j:	Pressure factors.
SO_2:	Sulphur dioxide.
r:	Heat of evaporation, kJ/kg.
s:	Entropy, kJ/kg K
S_i:	Scenario.
t:	Time interval, s
T:	Absolute temperature, K
TW:	Terrawatts, 10^{12}W.
ΔT :	Temperature differential (K).
λ:	Latent-heat of PCM (J kg^{-1}).
ρ:	Density (kg m^{-3}).
Σ:	Energy density (J m^{-3}).
V:	Volume of the heat-storage tank (m^3).

List of suffixes

a	absorber
c	condenser
e	evaporator
fg	change of phase at constant pressure
g	generator
s	solution

Subscripts

e:	Electricity.
coolth	Cooling produced by the chillers.
T:	Heat.

Glossary

Absorption: The take up of a gas within the bulk of a solid or a liquid, or the take up of a liquid by within the bulk of a solid.

Absorbent: A material that, due to an affinity, extracts one or more substances from a liquid or gas medium with which it is in contact and that changes physically, chemically or both during the process.

Angelery: A vessel in which steam is condensed.

Availability: The proportion of the maximum number of required running hours of the year for which the CHP unit is expected to be operational.

Autogeneration: The generation of electricity by companies whose main business is not electricity generation, the electricity being produced mainly for that companies own use [3].

Carrier 16JB: A series of absorption chillers manufactured by *Carrier.*

CFC's: Compounds of carbon, fluorine and chlorine widely used in aerosols and as refrigerants, solvents and cleaning fluids. They are chemically inert and so have atmospheric lifetimes of over 50 years. They are also important greenhouse gases [21].

Coefficient of Performance: (COP) of an absorption machine is a ratio used to rate the energy-transfer effectiveness of the machine. For refrigeration, this is typically interchanged with efficiency. COP, defined in equation 7.1, is the amount of cooling divided by the amount of energy input required to produce the cooling [29].

Condenser: A heat exchanger in which vapour is liquefied by the rejection of heat to a heat sink.

Crystallisation: The freezing of the lithium bromide (LiBr) solution. This reduces or stops the flow of the solution in the absorption process.

Ebullient Cooling of an engine involves natural circulation of the jacket's cooling-water during which the coolant undergoes a phase-change. The systems are simple and have low operating and maintenance costs.

Effects: Absorption machines are categorised by the number of *effects* or by the number of *stages*. An effect refers to the number of times the input heat is used by the absorption machine, either directly or indirectly [17].

Electrical efficiency: The percentage of the gross calorific-value of the primary fuel input, burnt per hour in the gas-fired CHP unit, and which appears as electricity generated during that hour.

Evaporator: The part of the refrigeration system in which the refrigerant is evaporated, absorbing heat from the contacting heat-source.

Fuel-efficiency factor: A parameter used to indicate how the fuel consumption varies under part-load conditions for the for a CHP unit.

Generator: The section of the absorption-chiller where the refrigerant is separated from the solution by the use of heat.

Gross calorific value: The amount of heat released/unit mass when the fuel is burnt, and its combustion products are returned to the initial temperature (usually 25°C). At this temperature, water vapour (produced from the hydrogen in the fuel) will have condensed thus releasing the latent heat of vapourisation. Note that gross calorific values will be used throughout this thesis.

Hot-engine CHP unit: A CHP unit with engine modifications to allow it to operate at higher temperatures. The consequence of the modifications will be a slightly reduced electricity output.

Load Factor: The average energy consumption rate for a facility divided by the peak energy consumption rate over a given period of time.

Model: The mathematical model created to simulate the behaviour of the CHP system.

Modulation: The reciprocating engine of a small-scale packaged CHP unit can operate at fractions of its rated, full power-output, i.e. at part-load. This is achieved by excluding pairs of pistons from power generation in response to decreasing the heat-demand from the engine (for a thermally-led unit). Thus the CHP unit's output can be varied step-wise. The variation of output to match heat- and/or electricity-demand from the CHP-unit is called modulation.

Nominal Cooling Capacity: is the cooling capacity for the absorption-chiller at standard ARI conditions.

Outcome Factors: These are the factors which will be effected if the predicted scenario develops.

Pressure Factors: These are factors which can lead to the development of a particular scenario.

PTX Equilibrium Chart: A chart to graphically show the LiBr absorption process.

Refrigerant: A fluid used for heat transfer in a refrigeration system. The fluid absorbs heat at low temperature and low pressure and transfers heat at high temperature and high pressure, usually involving changes of state of the fluid.

Running hours: The number of hours (e.g. per day, week or year as stipulated) for which the CHP unit is operated.

Scenarios: Realistic descriptions of future possible states of the industry's strategic environment.

Simple pay-back period: Capital cost of the system divided by the annual financial savings resulting from its use.

Site: The considered location with local heat-and-power demands.

Solution: A mixture of two elements. For absorption systems, these will be lithium-bromide/water and water/ammonia solutions.

Stages: A stage refers to the number of evaporator/absorber pairs at different temperatures in an absorption machine. A single-stage system has a single evaporator/absorber operating at a constant or primary temperature. A two-stage system has two evaporator/absorber pairs, each operating at a different temperature [17].

Storage efficiency: Defined as the energy delivered by the storage system divided by the energy delivered to the storage system.

Strong Absorbent: This solution has a high capacity for absorbing the refrigerant at a given reference temperature. The solution contains a low level of refrigerant and proportionally high levels of absorbent. Otherwise known as a *concentrated solution* for Libr systems.

Thermal efficiency: The percentage of the gross calorific value of the primary fuel input which when burnt in the gas-fired CHP unit produces useful heat (other than that used for electricity generation).

Weak Solution: This solution has a low capacity for absorbing refrigerant at a given reference temperature. The solution contains a high level of refrigerant and proportionally lower levels of absorbent. Otherwise known as a *dilute solution* for Libr systems.

Chapter 1

Introduction: The Problem

The last two decades have seen dramatic changes across the world in public and governmental attitudes towards regional, international and global pollution issues. Views have been hardening with an increasing resolve to tackle the sensitive issues, which have to be addressed before significant progress can be achieved. Media coverage of the scientific phenomena such as global warming, acid rain and ozone depletion have played a significant role in this general change of attitudes. The ongoing - and now pressing challenge - for <u>all</u> is to provide a means of achieving acceptable economic growth for all nations without reducing or suppressing their quality of life (i.e. sustainable economic development). This task can be addressed in two main areas: The <u>first</u> is the more efficient use of scarce resources together with a considered move away from polluting processes throughout the developed world and the <u>second</u> is a sensible, generous and symbiotic attitude from wealthy (developed economies) towards emerging countries, allowing their economies to grow in a sustainable manner. This could be achieved in part by encouraging the exchange of technology and 'knowhow'. One specific area of modern economies - considered vital for their development - where there exists substantial potential for improvement, in terms of efficiency and pollution, is in the production of energy. Increasing production efficiencies in this field would have an appreciable benefit for all. The study of energy-efficiency forms the core of this research thesis, with focus placed on the examination of the potential for increasing energy-utilisation in small-scale Combined Heat-and-Power (CHP) systems.

Combined Heat-and-Power (CHP) is the simultaneous production and use of heat (usually in the form of hot-water or steam) and power (usually in the form of electricity). It is a mature technology, which has been used in industrial applications since the nineteenth century. The term CHP is synonymous with 'co-generation' or 'total-energy' often used in the European Community, the United States and other parts of the world where the technology is widely employed. CHP systems can convert fossil-fuels into usable energy with efficiencies of 80% (and above in some cases where additional heat recovery equipment has been installed) and its widespread use could contribute significantly to the conservation of energy.

As one of the oldest forms of electricity generation, an early attempt to utilise CHP by industry occurred in 1898 at the Singer factory in Clydebank, Scotland. A successful implementation of a large CHP scheme - which supplied steam to neighbouring shops, offices and factories - appeared during 1911 in Bloom Street, Manchester [30]. This type of system can be categorised as a District Heating (DH) system. DH networks allow the export of heat to the public for space and water heating under arrangements where the consumers are treated as individual customers and are charged at either a flat-rate or on the basis of metered consumption. Industrial CHP capacity was in decline during the period from the 1950s to the early 1980s. In the 1950s the total installed CHP capacity in the UK exceeded 3,000 MW_e, however by 1988 it had reduced to about 1,800 MW_e [31]. The main reasons for this decline were: reduced heat-to-power ratios in industry, changes in process operations and the restructuring of British industry during the recession of the early 1980s [32]. In spite of reasonable economic growth during the 1980s, industrial energy demand declined and by 1991 had fallen to more than 40% below its peak in 1970. Over the same period, service sector energy demand rose by 11% [33]. Additionally, in the 1970's and 80's CHP was perceived as a threat rather than an opportunity by the UK electricity and gas supply companies [34].

The unit oil-price shock of November 1973, and the subsequent fluctuations in energy prices changed the pattern of supply and consumption of energy stimulating interest in alternative-energy systems including CHP. By the end of 1974, the British Government established the CHP Group, under the aegis of the Secretary of State for Energy's Advisory Council on Research and Development, to consider the economically viable role of CHP in the United Kingdom and to identify the technological, institutional, planning, legal and other obstacles to the fulfilment of that role, and to make recommendations [35]. It wasn't until the beginning of the 1980's that small-scale units were first installed in buildings, with the early projects installed in hospitals and hotels, supported and promoted by the Energy Efficiency Office (EEO) [36]. The electricity supply industry in England and Wales was privatised in 1990 as part of the Conservative Government's overall policy of privatisation. The change was intended to bring competition to the market. The full effects of this restructuring on the CHP sector are still undetermined. By the 1990s the generation of electricity for parts of industry was shifting from remote power stations to on-site generation [37]. Currently, most of the existing UK CHP capacity is installed at industrial sites, with oil refining, chemicals, food and drink, paper and board, and iron and steel being the key sectors [38]. Approximately 6% of the United Kingdom's electricity is now produced via CHP [3], a relatively small figure when all of the benefits of the systems are fully considered. However, it is set to rise further as a result of a combination of drivers in the market-place.

Financial savings brought about by energy savings are usually the main inducements for new investors in CHP systems, consequently, much emphasis is placed on the pay-back period of the investment. However, the application of the technology has another major advantage: As a direct result of the more-efficient production of energy, the polluting emissions from the process of generation will be reduced when compared with conventional heat and power production.

CHP systems produce their greatest savings when they are operated at full-load, with all of the heat and electricity output utilised for as much of the year as possible. Systems which operate for less than 4,000 hours annually are unlikely to produce the necessary financial savings to make the investment viable [6]. Under ideal conditions the CHP units would operate 24 hours per day all year round utilising all of the energy produced. However, off-peak electricity rates make this uneconomical in most cases and the heat and power demand profiles are not usually constant throughout the day, week or year. The demand for energy often follows an erratic pattern throughout the day according to human or manufacturing routines. Furthermore, the demand will also change on a seasonal basis as a result of changing climate and lighting requirements or varying demand for a product or service. The usual way for CHP to overcome this problems is to seek to provide the base energy requirements at a particular site. The unit will commonly be sized to satisfy the average base heat-load at the site, thus ensuring that it will be operational - saving money and energy - for as much of the year as possible. A comprehensive practical guide to the evaluation, development, implementation and operation of CHP schemes is provided by **Griffiths** [23]. It documents many of the essential aspects of the technology and includes several worked examples of the feasibility of potential systems. CHP systems and their associated economic appraisals can be viewed on three broad scales: Large-scale - representing an electrical output of above $1MW_e$, small-scale - representing electrical outputs in the range $30kW_e$ up to $1MW_e$ and micro-scale for electrical outputs of below $30kW_e$.

An issue which appears to limit the number of useful applications for CHP is the hourly, daily or seasonal mismatch between the output of energy from the unit and the demand for heat and electricity from the site. This research investigates the following three technical aspects of CHP: (i) the potential for the integration of absorption chillers in small-scale CHP systems. Absorption chillers can utilise the waste-heat from the CHP units when not required, for example the summer season, to produce air-conditioning, other forms of cooling or a combination of heating and cooling; (ii) substituting two CHP units, with a marginally greater heat and power output, in place of one larger unit; and (iii) the utilisation of a thermal-energy storage unit to even out the mismatch between the requirement for heat and electricity by decoupling the two processes.

Absorption chillers applied to CHP systems.

In addition to maximum electricity utilisation, the productive use of all (or as much as possible) of the heat produced by the CHP units is a major objective for the successful application of the technology. Increasing the amount of heat which is productively used will benefit the economics of the systems. The issue of obtaining maximum heat utilisation for large-scale systems has been addressed in many pieces of research (see Fallek, Van Winckel and Malewski, Hufford, Tozer and James etc.). Large-scale CHP has been integrated with absorption chillers to increase heat utilisation during the summer season, when the heat output from the CHP unit might otherwise be wasted.

A general study of the benefits of applying absorption chillers to CHP systems was carried out by **Fallek** in 1986 [39]. The study concluded that the absorption cycle can operate on several types of heat sources and that this fact renders them ideal for heat recovery applications. Increased efficiencies of the absorption chillers in recent years continues to advance the prospects for the integration of the two technologies.

Thermally-driven aqueous-ammonia absorption refrigeration plants were the first systems to be integrated with CHP and create a number of operational CHP opportunities that in the past would have been scrapped for lack of thermal-load [40]. The authors **VanWinckel and Malewski** [40] reported in 1989 on one of many successful applications of absorption chillers (200 to over 6,000 tons) to large-scale CHP, which have been installed in the USA since 1983. The ammonia systems - which have been successfully utilised for almost 100 years - are particularly applicable to industrial refrigeration applications when the requirement is for evaporator temperatures from 0°C down to -55°C.

The benefits of applying gas-turbine CHP systems to a two-stage absorption chiller were discussed by **Hufford** [41] in 1991. The paper concludes that the bottom line in CHP is to optimise energy, as well as economic resources. Recoverable heat is too valuable to waste in inefficient processes. The high-efficiency two-stage absorption chiller using direct exhaust-gas, steam from the heat recovery boiler, or extraction steam from a turbine offer new opportunities to maximise CHP economics. These high-efficiency absorbers offer more chilled water for the same recoverable heat and provide opportunities to enhance the efficiency of the gas turbines that power the CHP systems.

The thermodynamic principles involved with the ideal absorption cycle are summarised by **Tozer and James** [13] & [42]. Some simple formulae were obtained for the cycle in a similar way to the Carnot cycle. The research includes the analysis of single and multi-stage systems for cooling and heat recovery. A review of the potential and limitations of absorption systems is documented, however, this is restricted to theoretical work including ideal solutions and refrigerants.

Another paper, also written by **Tozer & James** [43] was produced in 1994 and extends the previous work by examining both ideal and real absorption cycles. LiBr-water binary mixtures are considered for single and double-stage systems. An optimisation criteria for both types of absorption chillers is determined. The research continues with an introduction to combined heat-and-power presenting some general guidelines for the application of absorption chillers to these systems. The significance of the temperature and mode (i.e. hot-water or steam) of supplied heat-source is discussed. A correlation between cooling-water temperature difference (ΔT across the absorber and condenser) and COP is illustrated for hot-water temperatures of 90°C and 115°C for a 1400kW (400 TR) single-stage absorption chiller. It concludes by stating that the choice is between single-stage chillers (if the main design criteria is initial cost) and double-stage chillers (if higher absorption cooling efficiencies are required).

A third paper by **Tozer & James** [44], written in 1992 concerned large-scale direct-fired absorption chillers. The equipment under investigation combined the functions of heating and chilling, including the capability of simultaneous chilled-water and heated-water production. The direct-fired cooling equipment exploited the double-effect absorption process (requiring a higher temperature heat-source): This part was not relevant to the thesis as the point of focus will be the integration with small-scale CHP systems, which have a relatively low temperature heat source (i.e. usually below 95°C unless a 'hot-engine' is used). The main point of interest in this research is in the determination of the impact that absorption chillers might have on the environment (the core of Chapter 7's work). The conclusions were based on the findings from a previous piece of work [45], which determined the weighted emission of CO_2 for the entire process of electricity production including extraction, processing, transport, generation and distribution at 75.7 kg C/GJ of electrical energy (1987 supply average and equivalent to approximately 1kg CO_2/kWh_e. It was concluded for the large-scale system studied that absorption chillers are marginally better than centrifugal-chillers by 0 to 0.3%. The comparison only takes into account the equivalent CO_2 emissions due to plant operation and not global warming potential of refrigerants used in centrifugal chillers. This is a general study considering large-scale systems.

An application guide for absorption cooling/refrigeration using recovered heat is given in the ASHRAE document by **Dorgan** *et al.* [17]. Both LiBr-water (single and multi-stage) and ammonia-water systems are covered in this document with the emphasis being placed on the utilisation of a range of varying heat sources. The guide begins its documentation of absorption systems which can operate with source water temperatures of 95°C. This would be the maximum temperature for recovered heat from a small-scale CHP unit. Consequently, this guide describes the application of high-grade heat-sources to absorption chillers.

Thermal-energy storage applied to CHP systems

The issue of maximum waste-heat utilisation from CHP units is critical for the total system economics. The application of absorption chillers to CHP systems can improve their financial viability by utilising heat which would otherwise be wasted. However, the demand for cooling is irregular, following daily weather conditions. Declining demand would lead to surplus heat from the CHP unit resulting in less favourable economics. Consequently, an opportunity exists to store excess thermal energy from the CHP unit in a form allowing its subsequent use. This systems could potentially produce significant energy savings in cases where there exists a substantial demand for the energy which can be easily liberated from the thermal-energy storage unit.

Martyak [46] and [47] demonstrated how the two proven technologies of CHP and energy storage could be teamed up to decrease initial investment costs and increase annual energy cost savings. The study concentrated on large-scale CHP systems and presented two primary methods for the integration of the two technologies (i) Using the CHP excess electricity to charge the TES system via electric, centrifugal refrigerant equipment and (ii) using the CHP waste-heat to charge the TES via absorption refrigeration equipment. A third method is proposed by combining methods (i) and (ii). It was concluded that the most cost-effective method for a particular application depends on electricity and natural-gas utility rates, electricity utility sell-back rates, the existing central plant layout, and the electricity and thermal daily demand-load profiles for the facility.

For large-scale CHP plant - used for district heating systems - the utilisation of the two technologies has been an integral part of the system since the first district-heating systems were installed. The pipe networks, which distribute the heat store substantial quantities of energy. A study of a district-heating system in Malmo, Sweden in 1991 [48] examined the potential for utilising heat accumulators to increase energy utilisation. Several storage possibilities existed. If the electricity demand is high, while at the same time the district heating load is too small to use all of the heat from the CHP plant, it could be optimal to store heat from the peak periods and discharge the storage at off-peak times. Alternatively, it might be optimal to store heat at off-peak periods and use it at district heating peak times. The application of a predictive model indicated that the highest profitability is achieved by using the cheaper off-peak hours heat - due to the electricity tariff - for heating the domestic hot water and water used in the radiators. In conclusion, the there was little interest for the storage system in Malmo, where a large district heating grid is available as a heat sink. This is a result of the low economic value of the heat from the CHP plant, which is usually produced from waste and very cheap fuels.

A paper by **Somasundaram** *et al.* [49] in 1993 examined the potential for TES in large-scale power plants in the USA. The study examined gas-turbine plant and high-temperature heat storage applications. It concluded that high-temperature TES integrated in a natural gas-fired CHP facility allows all power generation to occur during periods of peak demand. The installed capacity of the prime mover is substantially larger than for a conventional CHP system. A CHP plant with a TES system sized for an 8-hour peak-demand period would provide 30 MW_e of peaking capacity compared to a similar conventional CHP system, which would provide 10 MW_e of base load.

The viability of the integration of the two systems was further demonstrated in Japan by **Ito** *et al.* [50]. This is a small-scale system with a plant mixture of electric and absorption refrigeration equipment, oil-fired absorption chiller and oil-fired boiler. The effect of the heat-storage unit on the CHP system was investigated using a mathematical programming model. A case study approach was adopted to determine the daily and long-term operational policy for the installation of the system at a hotel. The hotel's energy demand profile was estimated using 12 representative days of the year. The authors concluded that (i) their method enabled easy and rational determination of operational policy for the integrated system, (ii) the optimal operational policy is to repeat the charging and discharging of the heat store frequently in order to reduce heat losses from the heat-storage tank, (iii) The installation of the heat storage tank together with the use of the optimal operational policy will reduce the daily and annual operational costs of the total plant and (iv) The volume of the heat storage tank will influence the long-term economy of the total plant. Therefore, there exists an optimal volume of the heat storage tank, which will minimise the annual total cost depending on capital cost of the heat storage tank and the fuel price.

A further paper by **Somasundaram** *et al.* [51] in 1993 documents some of the TES systems that are readily applicable to be combined with CHP and provides an update of the current status of these systems. The work concludes generally that TES can help CHP meet the challenges of the 1990s by increasing the flexibility and performance of CHP facilities. Another paper produced a year earlier [52] in 1992 undertook a cost evaluation of diurnal thermal energy storage for CHP applications.

Aims & Scope of the Investigation

The technical part of this research investigates the viability of three different types of CHP systems. The subject of the literature and research already documented in this chapter relates mainly to the application of TES and absorption chillers to large-scale CHP systems. Research which covers the application of these technologies to small-scale systems is limited and that which does exist usually concentrates on the upper end of the indicated size range. The research presented in this thesis aims to fill a small-part of the current gap in relevant literature. Therefore, this study will concentrate on small-scale gas-fired reciprocating CHP units in the UK. The core of the research aims to determine, if and how, the integration of CHP with two different technologies can produce operational systems, which can offer tangible advantages for potential users.

Non-technical research

The nature and scope of this research dictates that non-technical subjects such as financial and market appraisals will be integrated throughout the entire thesis. A vital question concerning the future of the UK CHP industry requires a more detailed analysis. The hypothesis put forward for this requires the study of the UK electricity industry. This is because the economic viability and consequently the market for CHP is highly sensitive to events within the electricity generation, transmission and supply sectors of the industry. The selection of three scenarios is achieved via the application of existing management techniques in a new manner. The scenarios - constituting either the most likely or the most influential events occurring, which would have the most significant effects on the development of the CHP industry to AD 2017 - are developed and analysed. The result of this study will be to describe the most favourable circumstances, within the electricity industry, for the future development of small-scale CHP in the UK.

Technical Research

The overall aim of the technical part of the investigation is to appraise the benefits offered by three separate CHP systems. In order to present a structured approach to the solution of this task, the problem is presented as three separate hypotheses:

- Can two CHP units in place of one single and larger unit produce significant benefits without lengthening the pay-back period?
- Can the utilisation of thermal-energy storage economically benefit small-scale CHP systems?
- Can absorption chillers provide significant environmental benefits to small-scale CHP systems?

Each piece of technical work is studied separately with the conclusions documented at the end of each relevant chapter.

CHP: Two-unit system

The first system proposed will apply two (smaller) CHP units in place of a single (larger) unit, with similar total electrical and heat outputs. This would enable the two units to be sized differently so that the primary (larger unit) can be operated to satisfy the base demand for energy while the secondary (smaller) unit is operated at peak times. In order to discover whether the two-unit system can produce energy and economic savings together with operational benefits over-and-above a single-unit system a predictive model is developed to compare the behaviour of the two systems. The study will investigate the potential for the two-unit system at five test-sites and will utilise spark-ignition reciprocating engines as the prime movers.

CHP & Energy Storage

The range of applications for CHP could be further increased if the generation of electricity could be decoupled from the generation of heat. TES can decouple power generation from the production of process heat, allowing the production of dispatchable power and the full utilisation of the thermal-energy available from the prime mover. This investigation will seek to determine the fundamental criteria, which will effect the technical and economic viability of the integrated system. Furthermore, the environmental benefits (in terms of CO_2 emissions) arising as a result of the application of the system will be quantified. Finally, an operational example of an integrated small-scale CHP and thermal-energy-storage system will be presented with the benefits recorded and analysed. Provided that the excess supply of heat from the CHP engine is transfered to the TES unit and later utilised at the site, then the system will deliver energy and monetary savings. However, achieving these savings in a cost effective manner is the challenge for the proposed system. In the commercial world only a system which has a relatively short pay-back period will be considered, and it will then have to compete with other potential capital investments offered throughout the company. The potential for electrical-energy storage will not be examined in any detail because it is considered that where the site is connected to the grid, a more effective solution to excess electricity generation would be to export it to the grid for transmission to another energy user.

CHP & Absorption chillers

Most of the documented cases for integrated CHP and absorption chiller systems involve the use of large-scale CHP units. The application of absorption chillers to small-scale CHP systems is relatively new, with very few on-site installations. The systems are currently not widely proven. However, they may have the same potential for increasing energy, economic and environmental savings as do the larger integrated systems. Many of the issues which face these systems have been addressed. The work in this chapter seeks to investigate the technical, economic and environmental potential for small-scale integrated CHP and absorption chiller systems, and present documentation of an operational case-study of the proposed system.

The aim of this study will be to try to determine if the integrated system can produce economic, energy or environmental savings (in the form of CO_2 displacement potential), when compared with vapour-compressions systems. In addition to the study of the appropriate CHP units, it is necessary to document the basic operational principles of the absorption systems, before the more specific points which are concerned with its successful application to CHP units are considered. The study will concentrate on the application of LiBr absorption chillers to small-scale CHP systems. The temperature of the hot-water from the CHP unit will be a critical factor for the determination of the capacity of the chiller. The temperature of the returning cooling-water from the cooling-tower will determine the Coefficient of Performance (COP) and capacity of the chiller. Chilled-water temperatures will also determine the size of chiller required for the specific application. Throughout this research average gross calorific values will be used where applicable.

Research Methodology

The four separate research questions are presented in Table 1.1. The same research methodology is applied to each of the three technical parts of the thesis.

Technical Research

For each of the three technical pieces of research a hypothesis is presented and tested. Three questions are posed:

(1) **Is the proposed scheme practical?**
(2) **Will the proposed scheme save energy, emissions or achieve other benefits?**
(3) **Is the proposed scheme economically viable?**

The solutions to the above will be achieved by the following:

(1) **Research of the technical area.**
(2) **Development and testing of a predictive model.**
(3) **Validation or demonstration where possible.**

QUESTIONS: DICTATING THE HYPOTHESIS	**RESULT METHODOLOGY**
Will two CHP units in place of one produce significant benefits?	1) Develop a predictive model. 2) Test on cases. 3) Predictions & conclusions
Can the utilisation of energy storage benefit small-scale CHP systems?	1) Research energy storage. 2) Develop model & test on cases 3) Predictions & conclusions
Can Absorption Chillers produce less CO_2 emissions than VC systems?	1) Research absorption systems 2) Develop model & test on cases. 3) Predictions & conclusions
What future for CHP in the UK electricity industry up to the year AD 2017?	(1) Research industry & determine the strategic environment & competitive forces. (2) Predict 3 likely scenarios. (3) Determine the effect on the CHP market.

Table 1.1: Four research hypotheses

Non-technical Research

The main objective of this part of the research is to determine which factors are crucial for the continuing expansion of the UK's CHP industry and market. This will lead to predictions for the prospects for growth for the CHP market over the next two decades. New empirical data will be presented for potential developments of the industry in a unique management orientated analysis. This will be achieved by undertaking a detailed study of the UK's electricity industry's background and history. Additionally, a breakdown of the companies involved and the process of trading electricity within the industry will be presented. The results from the non-technical research are achieved through the use of several strategic tools (i.e Porter's five-forces model, S.T.E.E.P. analysis and scenario planning) and the results from a questionnaire, which was specifically designed for this study. The survey - by way of the questionnaire - solicited the opinions of 'industry specialists' concerning cause-and-effect relationships for the electricity and CHP sectors of the energy market. A more detailed description of the research methodology involved for this chapter is given in Section 2.2.

Thesis Layout

Chapter 2 provides an overview of the electricity industry in the UK and satisfies the requirement for the management element of the EngD. thesis. The objective of this chapter is to determine how changes to the electricity industry can effect the prospects for the expansion of the CHP market. This objective is achieved through the analysis of several scenarios for the electricity industry to the year 2017. Three scenarios will be studied in detail leading to predictions for the development of the CHP sector. Three main management tools - porters five-forces model, S.T.E.E.P. analysis and scenario planning - have been adapted to assist with the completion of the research objectives for this chapter.

The technology involved with electricity generation is introduced in Chapter 3 as the background for the CHP sector. Emphasis is placed on the overall generating and transmission efficiencies. The technology of CHP is introduced on three scales (i) large-scale (i.e. greater than $1MW_e$), (ii) small-scale (i.e. $30kW_e$ up to $1MW_e$) and (iii) micro-scale (i.e. below 30 kW_e). Several of the technological aspects of large-scale CHP are discussed briefly before the main emphasis is quickly moved to the field of small-scale CHP and the relevant prime movers. The final section of Chapter 2 examines the CHP market in the UK.

The economic and operational benefits of installing two small-scale CHP units in place of a single (larger) unit are determined in Chapter 4. The operation of the two units is predicted by a computer model and the economic pay-back periods determined are compared for the two types of system.

Chapter 5 examines the potential for integrated small-scale CHP and (TES) systems.

The study is structured in three sections (i) the introduction of energy storage as a technology and it application to small-scale CHP systems, (ii) the development of a predictive model, which is used to determine the potential for heat-storage at five test sites and (iii) a study of the technical, economic and environmental benefits associated with the application of this type of system.

The potential and viability of integrating small-scale CHP and absorption chiller systems is investigated in Chapter 6. The overall approach is similar to that adopted in Chapter 5, which begins with an overview of absorption chillers and the technology involved with applying these systems to small-scale CHP. A predictive model is then developed to determine the energy-utilisation, economic and environmental benefits produced by the integrated system at a local hospital. The final section investigates the CO_2 displacement potential at an operational example of this system at a site in to south-east of England.

Chapter 7 completes the thesis by summarising the findings of the main technical and non-technical research and makes some concluding remarks. Finally, any proposals for future research to be carried out for each of the sections studied is presented.

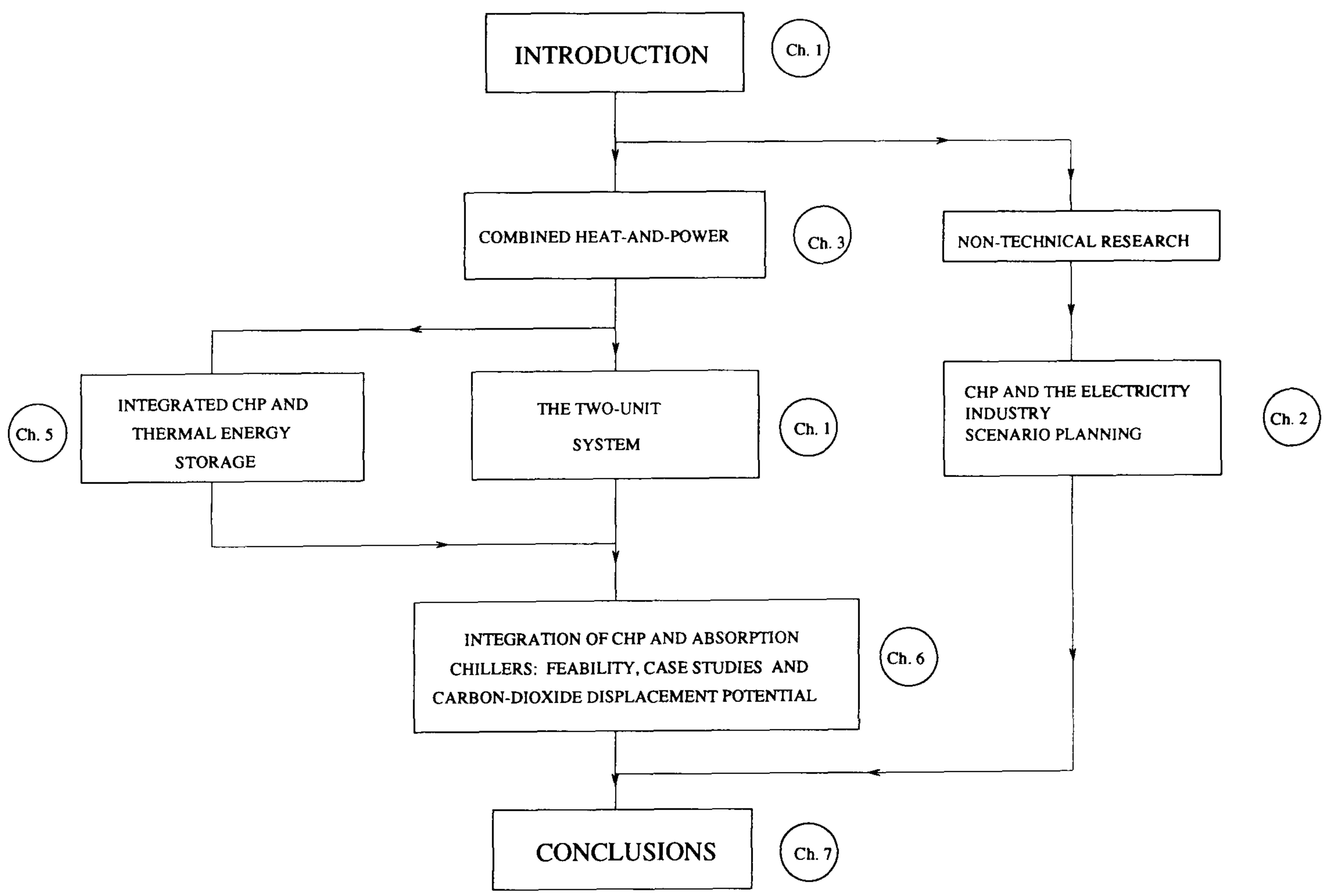


Figure 1.1: Thesis chapter structure.

Chapter 2

CHP & the Electricity Industry

Introduction

The technical, economic and environmental aspects of CHP are examined in detail in Chapters 3 to 6 of the thesis. Prior to this, the industrial and economic environment in which CHP must operate is now examined. This will be achieved by studying the UK's electricity industry's competitive environment. The main objective being to predict the prospects for growth for the CHP market over the next two decades and to determine, which factors are crucial for its continuing expansion. New empirical data will be presented for potential developments of the industry in a unique management orientated analysis. This will be achieved by undertaking a detailed study of the UK's electricity industry's background and history.

The prospects for Combined Heat-and-Power in the UK are difficult to predict with any degree of certainty. This is in part due to the fact that the future for CHP is inextricably linked to the future of the Electricity Supply Industry (ESI) as a whole, which is itself an extremely dynamic industry. Consequently, a study of the electricity industry's history, strategic environment and the competitive forces acting in 1997 within it are presented in order to assist with the selection and development of three scenarios. These scenarios will be used as a means of forecasting the future for the UK industry and hence the future for CHP to the year 2017. All relevant industry factors will be reexamined for the year AD 2017 for each of the scenarios. The development of each scenario will present a general view of the future potential positive or negative effects on the CHP market. The views of 'industry experts' were sought - via the completion of a questionnaire - to lend support to the predictions presented for the development of the UK CHP sector to AD 2017 - see Figure 2.1 for a guide to the order and structure of this research.

The specific methodology used for this research is documented in detail in Section 2.2. Figure 2.1 shows the the main tasks involved in this study.

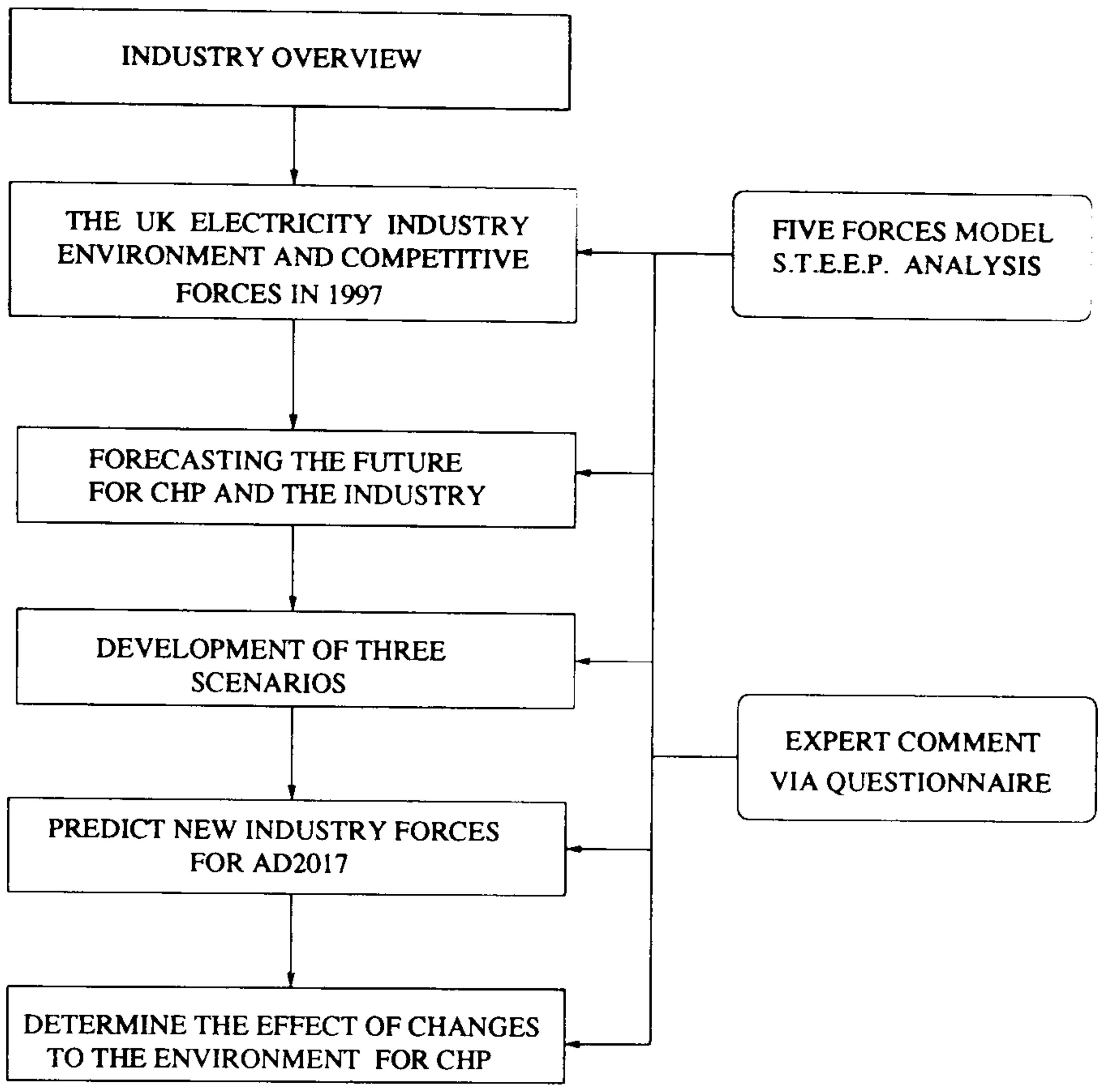


Figure 2.1: Strategic analysis of electricity industry: flowchart.

2.1 Industry Overview

The Electricity Supply Industry may be considered to encompass all the firms that compete directly with each other in serving the generation and supply of electricity in England and Wales. The electricity industry is one of the largest in the UK. In 1993 it contributed 5% of the total industrial output and about 1.5% of the total UK Gross Domestic Product (GDP). The capital assets of the electricity industry account for about 4% of the capital stock of the UK industries, placing it amongst the UK's top ten industries in terms of capital employed. Total capital assets employed were £25.8 billion in 1993/4 and capital expenditure amounted to £3.1 billion, representing about 4% of the UK's capital investment. In 1993 the industry employed 117,400 people equivalent to 2.5% of the total workforce in production industries [53]. These statements indicate the importance of the industry within the UK economy.

2.1.1 Industry History

The first UK supply of electricity was at Godalming in Surrey in 1881 and was followed in 1882 by the first generating station, which was constructed at Holborn Viaduct, London. In the 1930's the national distribution and transmission system emerged. As the industry expanded it became increasingly fragmented with between 500 and 600 private companies involved by the late 1940's. The 'state' increased its control over the expanding industry, culminating in its complete nationalisation in 1947. The fragmented industry had been considered wasteful with over capacity. Nationalisation helped to rationalise the industry and provide security of supply with a small number of large generators now producing electricity and hence utilising the economies of scale. The opportunities for small and independent generators - such as CHP - were negligible.

In 1979 a new Conservative Government was elected. Their manifesto included a programme of privatisations, which was to include the ESI. Consequently, a whole new industry structure for the ESI was created in preparation for privatisation, which occurred on 31st March 1990. Its structure was intended to encourage new entrants, increase competition and reduce electricity prices while at the same time increasing choice and service for all customers in the market. The privatisation of of the electricity supply industry was very different from previous recent privatisations carried out by the Conservative government. The majority of these had involved merely a transformation from a government owned monopoly to a public owned monopoly (for example the privatisation of British Airways). The privatisation of the ESI was much more complicated, i.e. 12 area boards, the CEGB, the Grid and several generators. The industry was split into several generators and Regional Electricity Companies (RESs), who were now expected to compete with each other for their share of the market.

Prior to 1990, the nationalised electricity supply industry in England and Wales was operated in two sections (see Figure 2.2):

1. The Central Electricity Generating Board (CEGB) which was responsible for the majority of electricity generation.

2. The National Grid Company (NGC), which transported the power across the country from the point of generation to the area boards through its vast transmission system of pylons, transformers and cables.

Privatisation

The primary aims of privatising the industry were to introduce choice to all of the UK's 23 million customers and encourage competition thus reducing prices. Consequently, a framework had to be put in place to facilitate this. This would be achieved by opening up the market to new generators and suppliers in much the same way as British Telecom had to open up its communications network to competitors. The whole of the ESI network would eventually be open for any generator or supplier to sell to any consumer and the change was staggered in three phases.

In March 1992 the first of these phases opened up the market to all consumers of 1MW and above. This limit was lowered to 100kW in March 1994 bringing more consumers the choice of who would supply them with electricity. In 1998 the final phase will result in the limit being scrapped completely with every user liberated to buy from any supplier. The operation of the new system will not be straightforward and the changes have in part lead to a great deal of uncertainty in the market about future electricity prices. It was originally intended to instigate the final phase of the transition at the same time. However, because of the large number of customers involved in this stage, OFFER is now considering plans to bring in a step by step change for customers over the months April to September 1998.

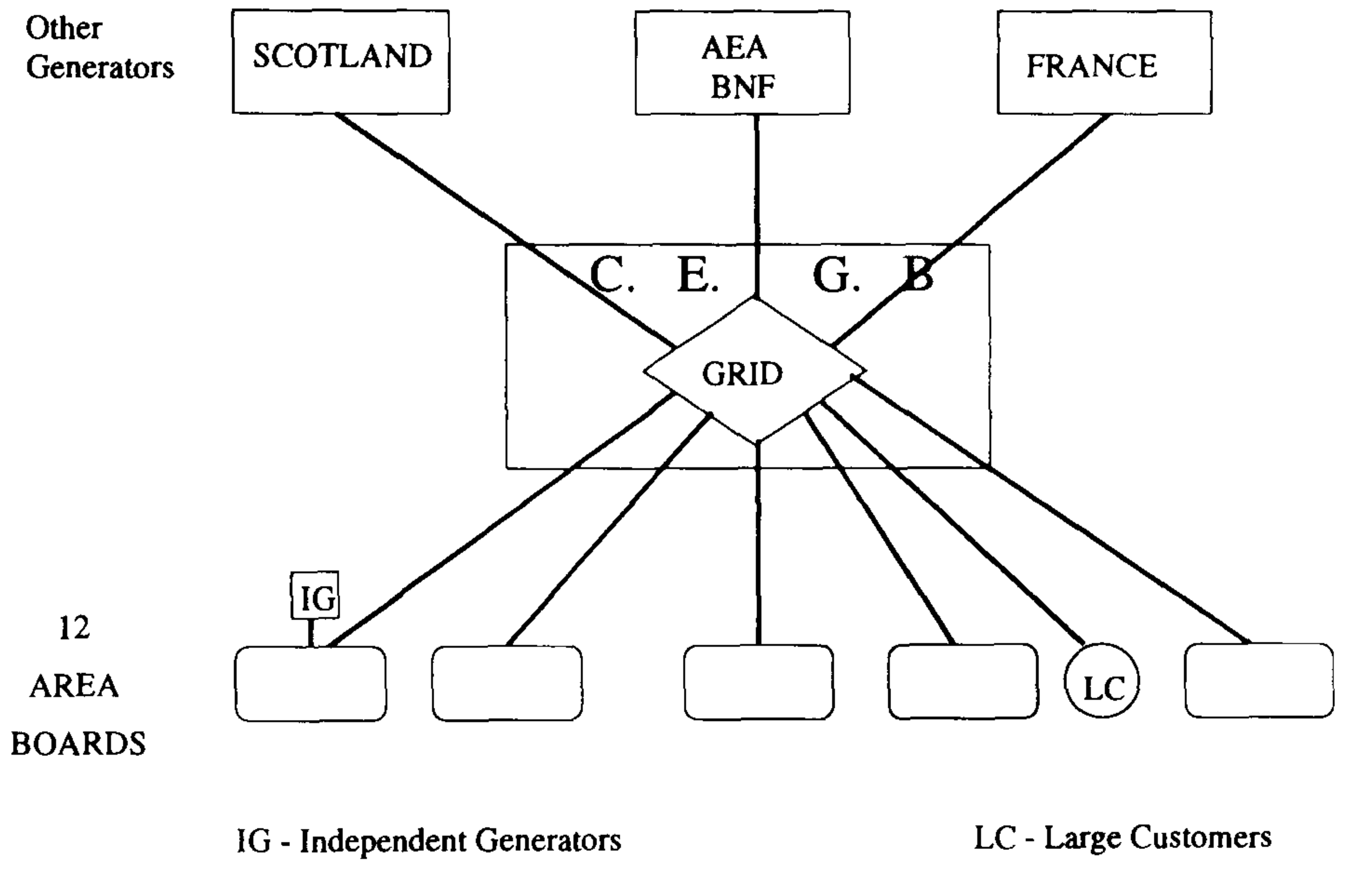


Figure 2.2: Electricity industry prior to privatisation on 31st March 1990 [1].

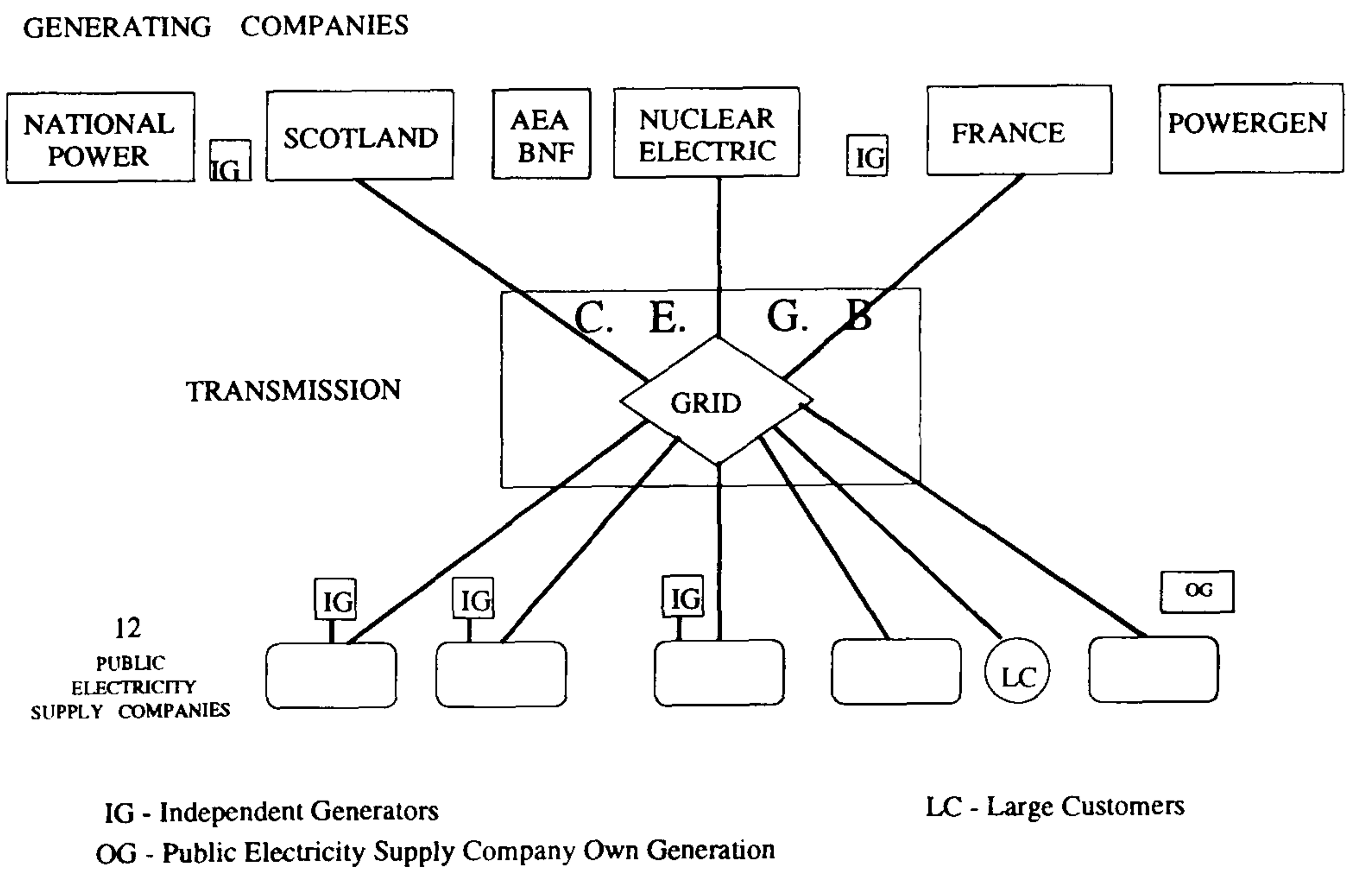
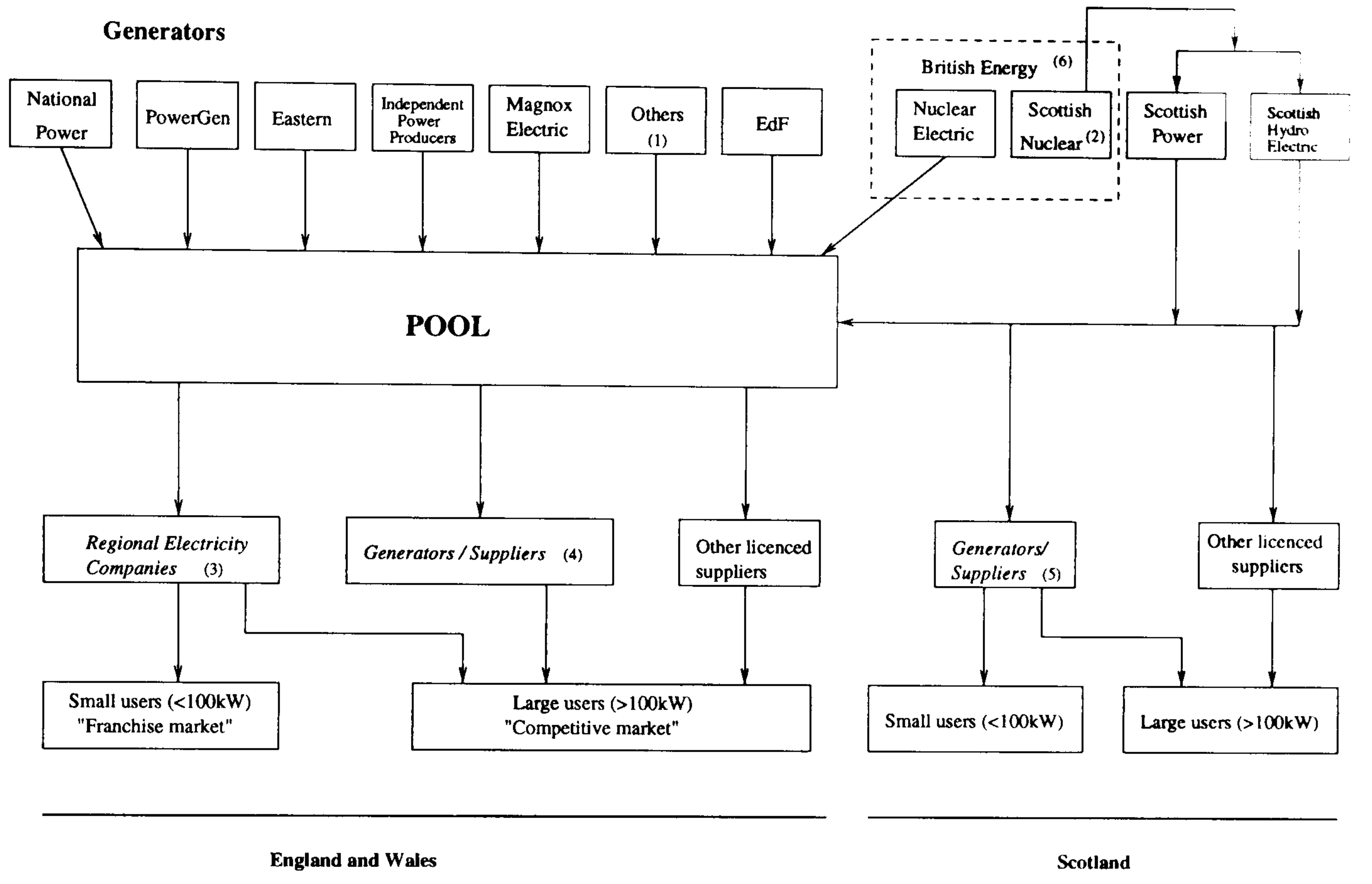


Figure 2.3: Electricity industry after privatisation on 31st March 1990 [1] and [2].

Figure 2.3 illustrates the structure of the electricity industry in 1990 following its restructuring. Privatisation split the CEGB into two fossil fuelled generators (National Power and PowerGen), one nuclear generator(Nuclear Electric) and the distribution network (National Grid). The area boards in England and Wales became twelve regional electricity companies.



(1) Including some autogeneration
(2) Other small generators also supply electricity to Scottish Power and Scottish Hydro-Electric
(3) Comprising: East Midlands Electricity, NORWEB, Eastern Electricity, SEEBOARD, London Electricity, SWALEC, MANWEB, SWEB, MEB, Southern Electric, Yorkshire Electricity.
(4) Comprising: National Power, PowerGen, Scottish Power, Scottish Hydro-Electric, Magnox Electric, Nuclear Electric.
(5) Comprising: Scottish Power, Scottish Hydro-Electric.
(6) British Energy is holding company for Nuclear Electric and Scottish Nuclear.

Figure 2.4: The structure of the electricity in Great Britain in 1997 [3].

Since privatatisation, the development of the industry has continued. In 1997 there are now many different generators. The roles played by each of the companies involved in the industry have also changed dramatically. Generators have began to supply electricity and RECs have started to generate. Additionally, each of the companies has acquired an interest in the supply of gas as well as electricity.

2.1.2 The operation of the industry

The practical operation of the industry can be seen to involve four main functions which will be discussed in turn:

- Generation: The production of electricity.
- Transmission & Distribution: The transfer of electricity in bulk across the country and the delivery of electricity over the local networks.
- Supply: The acquisition of electricity and its sale to customers.

In addition, two new elements have been added to the structure of the electricity industry: 'The Electricity Pool' and the' Regulator'.

The generators in England & Wales

Generation comprises five main companies created by re-grouping the previously state-owned power stations, and independent generation companies. The main generators are National Power, PowerGen, Nuclear Electric, Magnox Electric and Eastern Group. Independent generators include CHP and other forms of internal electricity-only generation.

National Power are the UK's largest electricity producer generating around a third of the power for England and Wales with a total generating capacity of some 24GW. In 1992 National Power burnt 44 million tones of coal and 1.3 million tones of oil [54]. The company has a significant impact on the environment. As a result National Power is investing 1 billion pounds over a five year period on pollution reduction technologies such as flue gas de-sulphurisation equipment and low N_{ox} burner systems. The overall investment in new plant and equipment over the period 1993-98 will be around 2 billion pounds. However, electricity is still mainly generated from coal and oil combustion. PowerGen, the second main generator and similar to National Power although now a competitor in the electricity industry, undertakes many of the same functions as National Power.

The Nuclear Industry was initially held in public ownership following the privatisation of the rest of the electricity industry in 1990. This delay had occurred because of the concerns regarding the cost of decommissioning redundant plants. Following the Governments review into prospects for nuclear power in the UK in 1995, the decision was taken to transfer the UK's Advanced Gas-cooled Reactors (AGR)s and Pressurised Water Reactors (PWR)s to the private sector. Nuclear Electric is now the company responsible for these reactors in England and Wales and Scottish Nuclear Ltd. is responsible for the Scottish reactors. The industry was eventually fully privatised in July 1996 when when the holding company for these two concerns became British Energy. The other magnox reactors have remained in the public sector under the name Magnox Electric plc.

The remaining significant generator Eastern Group was originally Eastern Electricity following privatisation. However, Hanson Group took over the company and expanded its role in the market.

Transmission

In England and Wales transmission is the responsibility of the National Grid Company (NGC), which maintains and operates over 7,000Km of high voltage lines, 500Km of underground cables, 280 sub stations and more than 21,000 transmission towers. Electricity is transmitted from power stations to grid supply points which are connected to the regional distribution system of the twelve regional electricity companies. NGC also own 2.088 MW of pumped storage generating capacity as well as the inter-connectors between the systems in England and Wales and those in Scotland and France. The company administration is handled by NGC Settlements Ltd.

Distribution

The RECs are responsible for distribution to most customers. It is their main business activity and must be operated as a separate business from supply. They are governed by the terms of their Public Electricity Supply (PES) licences.

Supply

The RECs have an obligation to supply electricity to customers in their own authorised areas, but they may also supply customers in the competitive market nationwide. RECs have an monopoly of franchise supply, i.e. sales of electricity to customers with a maximum demand of less than 100kW, until 1998. They are referred to as first-tier suppliers. Customers with a maximum demand of greater than 100 kW may have a supply contract with a REC from another region, a generator or an independent supplier. These suppliers are commonly known as second-tier suppliers.

	Market shares by site, %							
Supplier	1990/91	91/92	92/93	93/94	94/95		95/96	
	1MW	1MW	1MW	1MW	1MW	100 kW	1MW	100 kW
1st Tier	72	64	68	63	56	75	48	67
2nd Tier	4	10	12	19	23	20	27	27
All Others	24	26	20	18	21	5	25	6

Table 2.1: Non-franchise market shares by sites supplied [19].

With more than three million customers, Eastern Group is the UK's largest regional supplier of electricity [55]. One thousand seven hundred of these customers are businesses in the competitive over 100 kW electricity market. Eastern Electricity has recently commissioned its first power station at Peterborough which can generate more than 360 MW of electricity. In addition to electricity generation, the company has a growing interest in gas supply providing 5,500 sites throughout the United Kingdom. These factors illustrate the effects of privatisation with each of the different companies in the industry extending their commercial activities to increase their competitiveness and profitability.

The other RECs are: Northern Electric, Yorkshire Electricity, East Midlands Electricity, London Electricity (LEB), Seeboard, Southern Electric, South West Electricity Board (SWEB), South Wales Electricity Board (SWALEB), Midlands Electricity Board (MEB), Manweb and Norweb

2.1.3 Key elements of the new electricity supply industry

With the physical structure (i.e. generators, suppliers and the grid) of the new electricity industry now in place, two further key elements were needed:

- The Electricity Pool
- The Regulator

Prices are set in the 'Pool' and the industry is regulated by the 'Regulator'. These elements were not required when the industry operated as a state owned monopoly without competition and with ultimate government control.

The Electricity Pool

The Electricity Pool involves the trade of electricity and is operated by the National Grid Company (NGC) through the administration of NGC Settlements Ltd. The Pool was created to ensure that demand is met by available generation at all times and at minimum cost, encouraging competition in the generating sector. It also includes handling appropriate payments flow from consumer to generator. The pricing of electricity consists of a number of different elements. The way in which the pool trades and sets the price will be described below.

The rate paid to the generators by the pool for each unit of electricity is fixed according to the system described below. The final rate paid by the pool is obtained from a combination of the following:

- Energy cost.
- Capacity payment.
- 'Uplift' payments.

Each generating station bids a price at which they are willing to generate electricity for each half hour of the following day. They also provide information on the available capacity of the station. The bid price is based on the particular running costs, maintenance requirements, fuel prices and the efficiencies of each station. These bids are then arranged in merit order. The position of each generating station depends on its bid price, its geographical position and ability to meet rapid changes in demands, but generally, the more-efficient (cheaper) stations are higher in the order. The Pool will accept a number of the bids for each half hour slot dependent on the predicted energy demand for that half hour. The final unit rate paid to all generators for each half-hour of each day will be based on the the price of the highest accepted bidder for each half-hour. This price for energy generation is called the "System Marginal Price" (SMP). In most cases, this price will be set by the highest cost coal-fired generating stations. The electricity produced by these stations will also be the first to be excluded by the pool if there is over supply on any particular day.

The theory behind marginal pricing is to encourage a plant to make energy available at as low a price as possible to ensure that the price is accepted by the Pool and the plant can continue to generate as scheduled. In an efficient market a generator will bid its marginal cost of production (effectively the fuel price), and receive its profit from the difference between the SMP and its bid price. The cost of energy production from pumped-water stations is relatively high and so these will only bid for peak rate supply each day and may or may not be used according to the level of demand. Nuclear Electric will usually bid the cheapest unit price each day as they cannot afford to be omitted from the supply of electricity unless absolutely necessary (i.e. in cases of maintenance or breakdown). This is because the nuclear reactor cannot easily be shut down, and must therefore produce electricity in any case.

Along with the actual energy cost, a 'capacity payment' is paid to generators to encourage them to make plants available to generate both in the short and long term. It is possible that if generation were only paid when actually required, there would be a shortfall of capacity in a colder than average winter. This would be because a plant that operated on few occasions might not be sufficiently remunerated.

The energy payment and the capacity payment together form the Pool Purchase Price (PPP) - the price at which generators sell their electricity to the Pool.
Finally, a basket of further payments is added to this price for services provided by generators beyond those paid for within the PPP. This basket is called 'uplift' which is added to PPP to set the price at which the Pool sells energy (to the RECs (or large industrial users). This final figure is termed the Pool Selling Price (PSP).

The Regulator (OFFER)

The Office of Electricity Regulation (OFFER) was set up by the government during privatisation. The prime function of this regulatory body is to ensure fair play for consumers by maintaining healthy competition in the marketplace.

2.1.4 The Non Fossil-Fuel Obligation/Fossil Fuel Levy (NFFO or FFL)

To encourage the use of energy derived from non fossil-fuel sources, a levy is imposed on all electricity produced from fossil fuels provided by licensed suppliers.

This requirement has been laid on each REC, under the terms of the 1989 electricity Act, until 1998 to secure a specific amount of electricity from renewable energy sources. The Non-Fossil Fuel Agency NFFA co-ordinates the purchase of privately generated surplus electricity resulting from the use of renewable energy sources, whereby the price is enhanced using funds from the levy. The fossil-fuel levy has been reduced substantially with the re-structuring of the nuclear power industry (once 10%, then 3.7% and now 2.2% from April 1997) [56].

2.1.5 National and international trade in electricity

International trade in electricity and connections between European countries has been increasing significantly in recent years [20]. Europe does not yet have one fully integrated system, but there are different interconnected systems, which have been developed separately due to geopolitical and technical factors.

Country	Input (GWh)	Export (GWh)
Belgium (B)	9224	5325
Germany (D)	38076	33895
Spain (E)	7632	2947
France (F)	2337	71680
Greece (GR)	1301	563
Italy (I)	39042	1219
Luxembourg (L)	5637	745
Netherlands (NL)	15549	3850
Portugal (P)	2570	1742
Austria (A)	8138	10275
Switzerland (CH)	18113	25143
Slovenia/Croatia (SLO/CRO)	2915	817
Ex Yugoslavia	403	490
GB	16078	25

Table 2.2: Electricity power flows in Europe - 1995 [20].

Four organisations currently manage the international exchanges of electricity. These are UCPTE (the Union for the Coordination of Production and Transmission of Electricity), NORDEL (Northern European countries incorporating Norway, Sweden, Denmark, Finland and Iceland), CENTREL (central European countries - Poland Hungary, Czech Republic and Slovakia) and CDO-IPS (Central Dispatching Organisation of the Interconnected Power Systems). The function of UCPTE is to facilitate and promote energy exchanges and harmonise operating methods in Western Europe in order to achieve the most efficient utilisation of power generation facilities and transmission systems. It covers most of Western Europe and the Balkans. In 1995 the total physical exchange of electricity between member countries of the Union for the Coordination of Production and Transmission of

Electricity (UCPTE) - founded in 1951 - amounted to 137 TWh (172 TWh including exchanges with non-member states) - see Table 2.2. This amounted to an increase of 11.3% on the previous year and represents about 11% of total electricity consumption in the UCPTE member countries.

Electricity can be transferred between Scotland and England and a link is due to be completed between Scotland and Northern Ireland. This will mean that electricity could be transferred from Northern Ireland to England via the Scottish inter-connector. The inter-connector between France and England supplied 16.44 TWh of France's nuclear generated electricity in 1995, which is equivalent to approximately 5.5% of the UK's 1994 consumption (296.2 TWh).

2.2 Research Methodology for the Industry's Strategic Analysis & Scenario planning

A strategic analysis of the UK electricity industry will be undertaken to identify and measure all relevant trends and forces that effect it. This analysis will be carried out in two stages (see below) and will include new empirical data on how the industry could develop. The analysis will be achieved with the aid of the following management tools:

- Five forces model.
- Analysis of Social, Technological, Economic, Environmental and Political (S.T.E.E.P.) factors.
- Scenario planning analysis.
- Survey of 'experts' opinions via a questionnaire.

The first stage of the analysis is partially subjective (see Figure 2.5), and uses the 'five forces' model, 'S.T.E.E.P.' and 'scenario planning' analysis to produce a trial questionnaire. The second stage is more objective (see Figure 2.6), and will undertake a pilot postal survey of the views held (in relation to CHP and the ESI) by 'industry experts' with the provisional questionnaire. The results from the pilot study will be used to develop the questionnaire further so that a wider postal survey can be carried out before undertaking the final scenario planning analysis.

The 'scenario planning' analysis is undertaken using the information gained from 'five forces' and S.T.E.E.P.' to develop five different scenarios for the future development of the industry to the year 2017. The views of 'industry experts' will be sought and incorporated with the analysis to assist with the predictions for the likely effects - as a result of the realisation of each scenario - on the ESI and specifically the CHP sector. A study will be made so that the scenarios can be ranked in order according to the likely magnitude of the effects on the future of the industry (see the probability and impact diagram in Figure 2.10). The aim is to reduce the study to three scenarios for further analysis. Industry forces will be predicted for the year 2017 together with the resulting implications for the CHP sector.

Questionnaire development:
The application of the 'five forces' model and 'S.T.E.E.P.' analysis will give rise to results, which could be viewed as partially subjective. This is because the analysis is undertaken by one writer with their own views and opinions. In order to increase the level of objectivity for this study the views of 'industry experts' were sought via a postal survey and used to validate the development and conclusions of the scenario analysis. The results from the questionnaire are incorporated into the full analysis and are used to indicate the level of likelihood of each specific scenario, as well as the degree of effect on the CHP sector as a result of the development of the specified scenarios. The management tools, introduced above will be used to aid the selection of appropriate questions for the questionnaire. Initially, a pilot study is undertaken (with a sample of 3) so that the results can be analysed and any ambiguity removed. The trial study also helped to determine how the questions might be interpreted and to ascertain usefulness of each of the questions before the wider study is carried out. This is an anonymous survey of opinions with the 'industry experts' selected from the CHP industry, manufacturer and technical organisations. The final version of the questionnaire was sent out to a sample of 14 with a total of 8 full replies. The questionnaire and the full results of the survey are presented in Appendix B.

Scenario analysis methodology.

The structure of the scenario analysis is illustrated in Figure 2.5, 2.6 and 2.7 and highlights the six separate stages of the analysis. The model described in equation 2.1 is required to provide a structured approach to the entire analysis and to aid the determination of the main objective - the 'collective effect' on the CHP sector (described by equation 2.1) of various changes to the electricity industry. The results from the questionnaire will be used to predict estimates for several of the stages and verify the selection of issues used in the other stages. The six elements of the model (scenario analysis) are described below:

Pressure Factors ($\mathbf{PF}_j$):
The realisation of any one particular scenario is determined by what are termed 'pressure factors'. This is a new term, developed specifically for this study and is required to illustrate the significant influencing factors. These 'pressure factors' are the forces acting within the industry's environment. They may give rise - either separately or collectively - to the development of the identified scenario and are derived from a combination of S.T.E.E.P. analysis, the results from the questionnaire or the authors own opinions.

Scenarios (S_i):
Are descriptions of possible future states of the electricity industry environment. This research will initially include the study of five different scenarios before two are eliminated from the study, leaving three for more detailed analysis. The scenarios are developed from one or more of the issues raised as a result of the S.T.E.E.P. analysis.

Likelihood (L_I):
The estimated probability of the stated scenario actually developing as a consequence of pressure factors is described as the 'likelihood'. The estimates for this factor are derived directly from the results obtained from the questionnaire - see Appendix 2B.

Outcome Factors (F_n):
Following the development of the scenario, it is likely that the industry's environment will change in one or more ways: 'Outcome Factors' specify these possible changes. The likely effect of the development of each element of any one scenario or the entire scenario is measured through the examination of the five forces in 1997. By predicting how these forces might change over time or with changing circumstances, the effect of the development of each scenario is predicted.

Effect on CHP (E_f):
The effect of the 'Outcome Factors' on the CHP market. Certain questions were posed in the survey to determine if specified changes to the ESI would lead to a predetermined outcome for the CHP sector. The results from the questionnaire were fed into this part of the scenario analysis to predict and measure this effect.

Collective Effect on CHP (CE_{CHP}):
A further development of the outcome factors'. An appraisal of the impact on the CHP market, as determined by an in-depth analysis of collective effect of each of the other five elements. The predictions for this factor are derived directly from the results obtained from the questionnaire - see Appendix 2B.

The six stages identified above and in Figures 2.5, 2.6 and 2.7 will be expanded for each scenario and conclusions gathered from this analysis. Equation 2.1 illustrates the relationship between each stage.

$$CE_{CHP} = f_1(E_f, S_i, L_i, F_n) \; and \; S_i = f_2(PF_j) \qquad (2.1)$$

Where CE_{CHP} is the collective effect on CHP, E_f is the effect of CHP, S_i is the scenario (which is a product of the pressure factors - PF_j), F_n represents the outcome factors and L_i the likelihood.

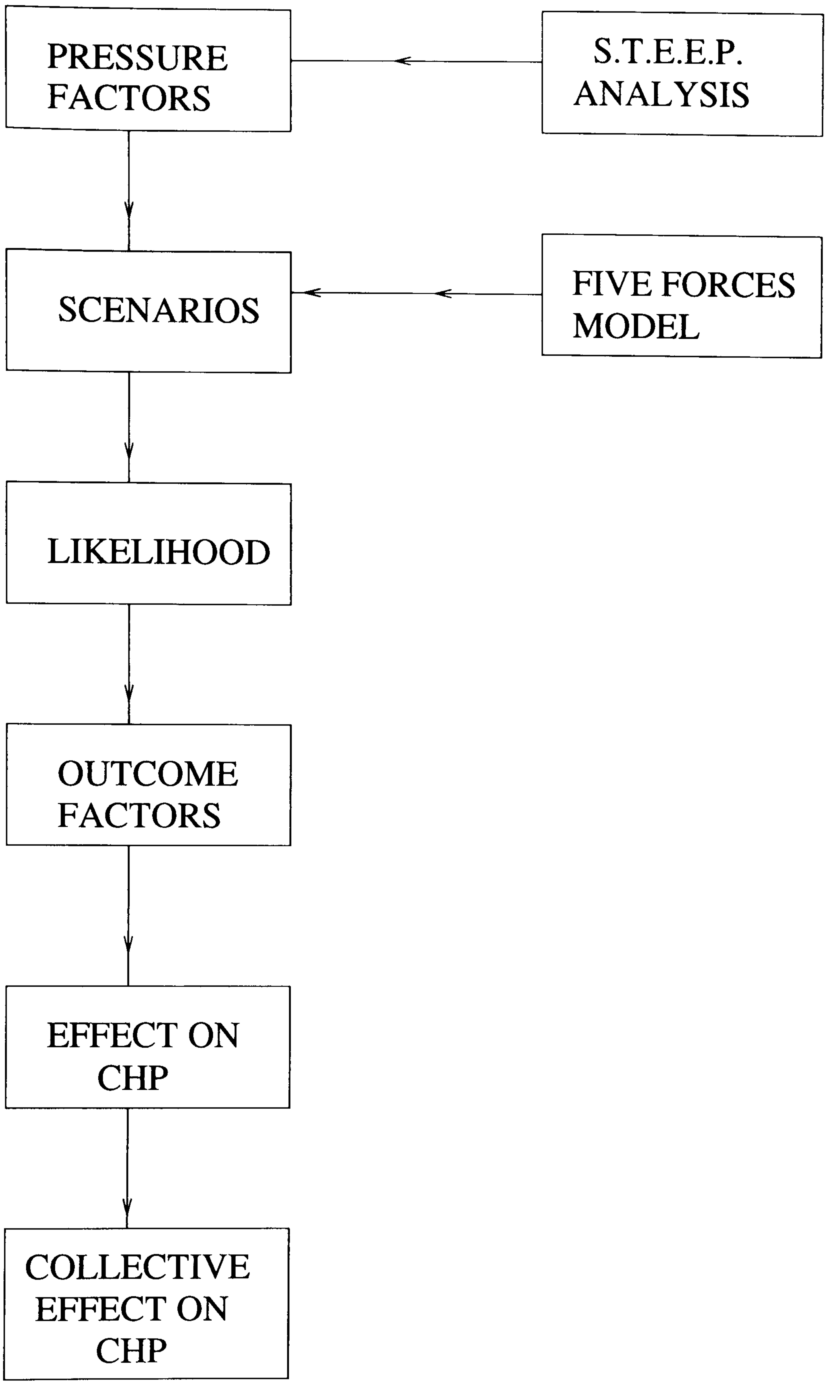


Figure 2.5: Flowchart showing the inputs to the research methodology for the strategic analysis of the CHP/ES industry's - subjective approach.

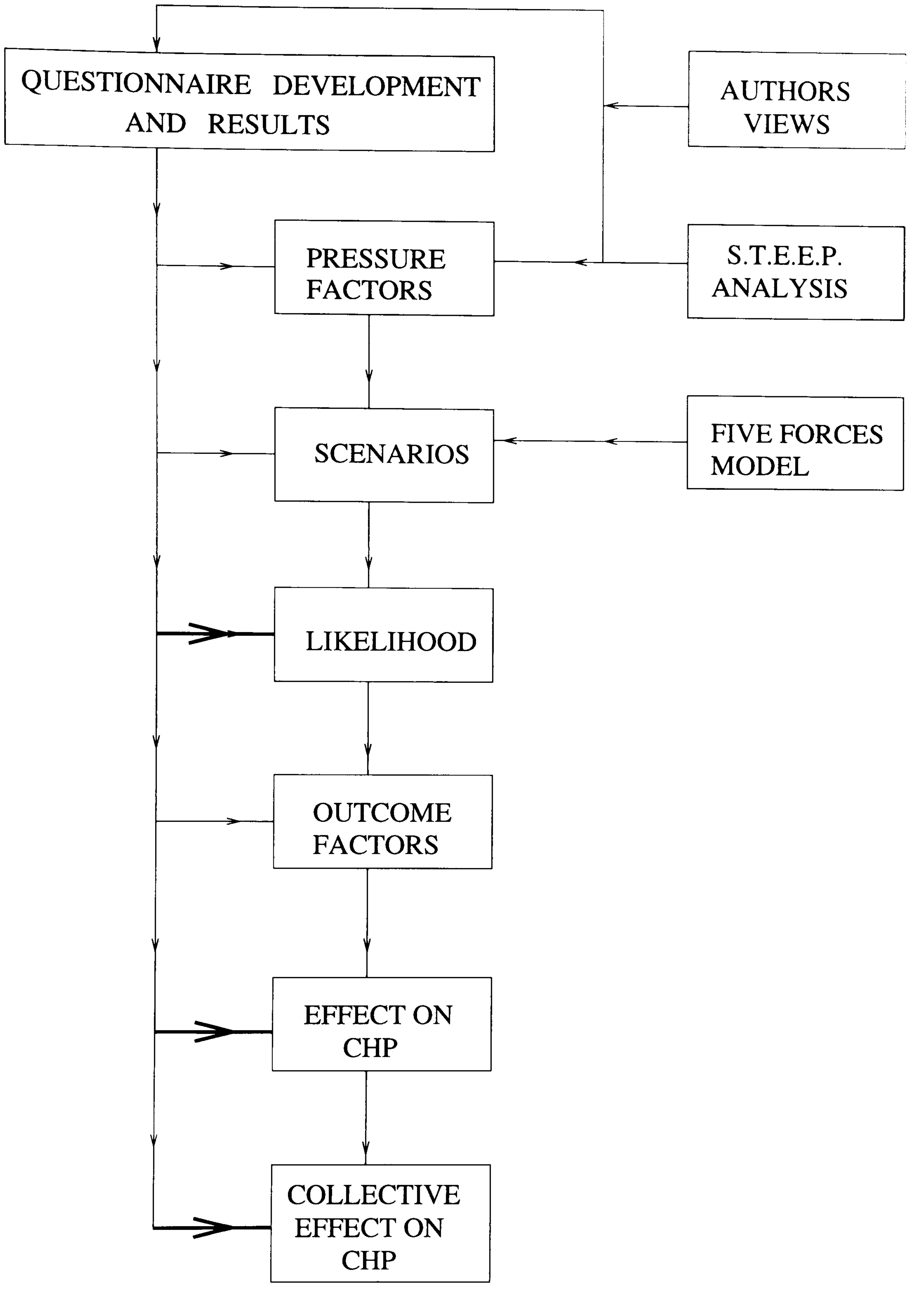


Figure 2.6: Flowchart showing the inputs to the research methodology for the strategic analysis of the CHP/ES industry's - more objective approach.

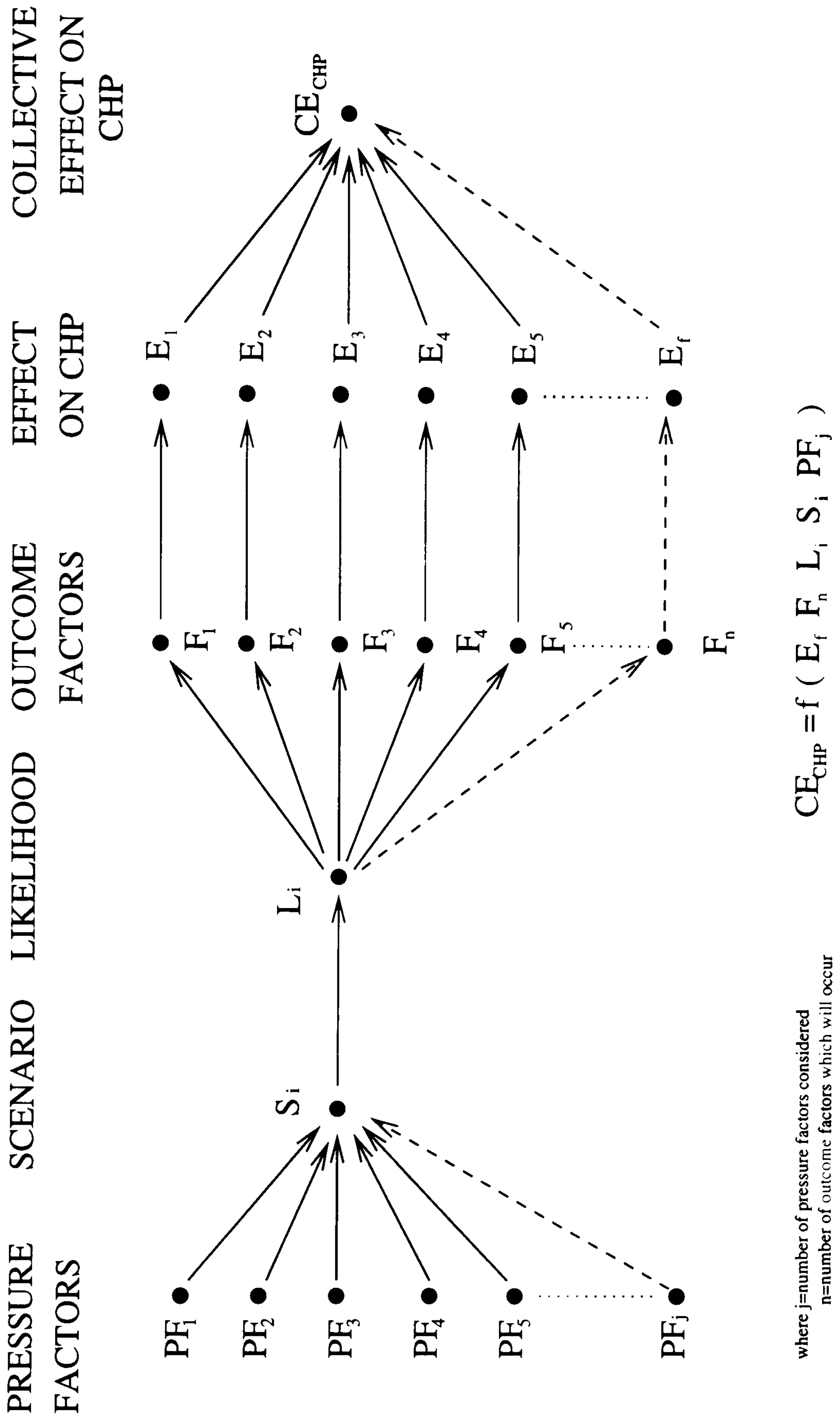


Figure 2.7: Scenario analysis plan.

2.3 Analysis of the Electricity Industry's Competitive Forces and Environment.

Many different companies compete in the electricity industry for a share of the total market - see Chapter 3 for a detailed analysis of the market breakdown. The relevant industry environment is broad and encompasses many different and varying features such as political, social and economics factors. Porter [57], stated that forces, which operate outside the industry may be just as important as those which act within it, therefore, it is also necessary to look outside the industry for a complete study of the subject. The main objective for this chapter is to forecast the future for CHP within the ESI. However, it will first be necessary to determine how the ESI operates in 1997. Analysing the competitive forces in this dynamic industry will require an understanding of all of the relevant factors together with a method for predicting and measuring any likely effects should these factors change at any time.

2.3.1 Competitive forces within the industry

The Five-Forces model, which was developed by Porter, helps to gain insights into the structure and competitiveness of the industry in 1997 and beyond. It achieves this through the examination of five specific forces industry rivalry, power of the buyers, threat of substitutes, power of the suppliers and the barriers to entry - see Figure 2.8 for a summary of the state of the competitive forces in the ESI in 1997.

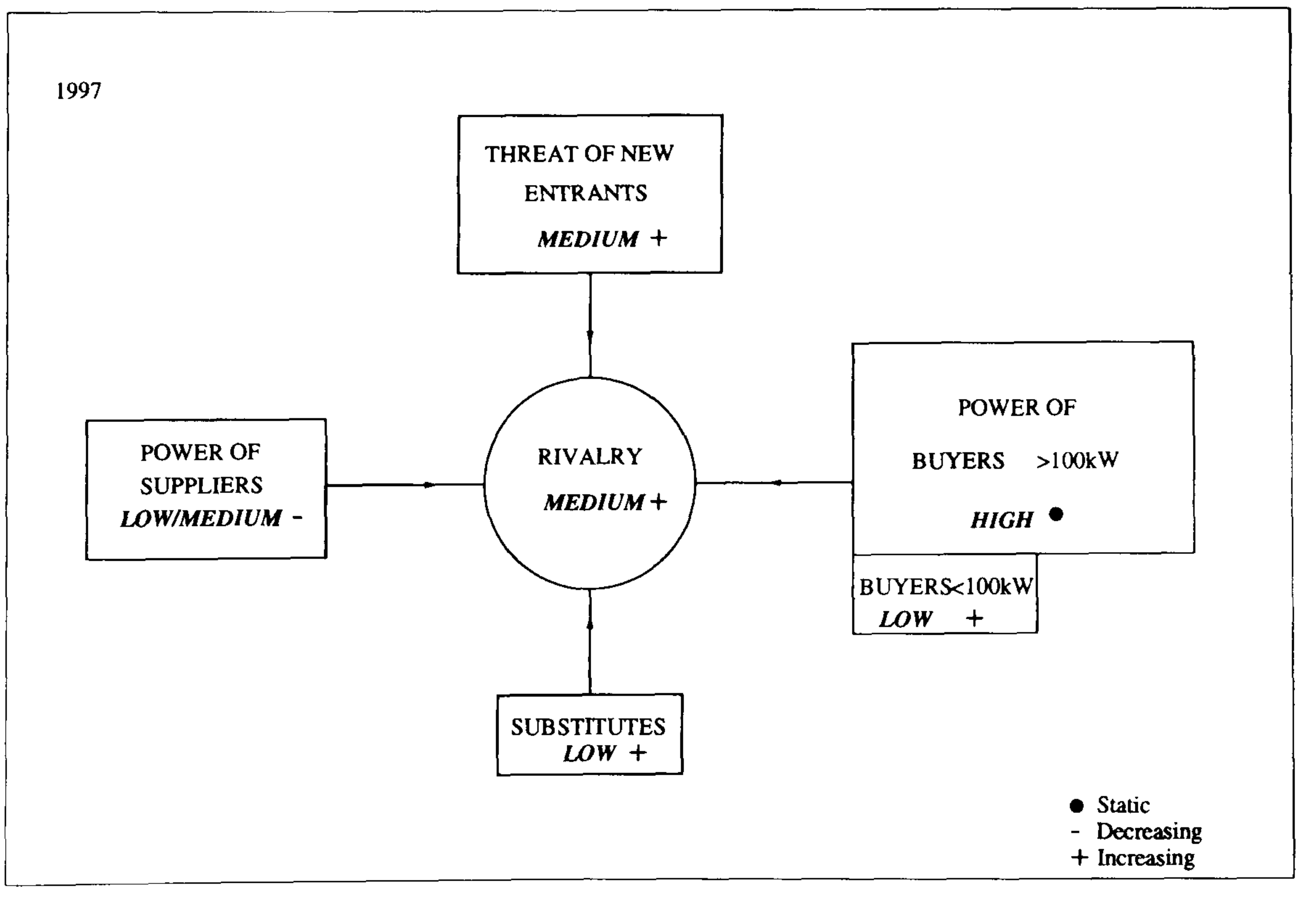


Figure 2.8: Porters five forces 1995.

Figure 2.8 illustrates how the five-forces model can highlight the state of competitiveness within the industry in 1997. The measurement of the degree of threat or 'rivalry' is specified in terms of **'high'**, **'medium'** and **'low'** and will also have an indication of movement attached to it (eg. increasing (+), decreasing (-) or static (o)).

The relevant aspects of each of the five forces will be discussed and quantified below.

Threat of new entrants

The threat of new entrants is a function of both barriers to entry/exit and the anticipated reaction from existing competitors that an entrant to the electricity industry can expect. In 1997 the 'threat of new entrants' to the industry is considered by the author to be **'medium'** and increasing for the following reasons.

Privatisation has brought many changes to the industry with the 'generators' moving into supply and the RECs moving into generation. Increasingly, the new entrants are large users who are now generating their own supplies in-house (auto-generation).

New entrants can build smaller and more energy-efficient gas-fired plants to compete on cost with the duopoly of the two privatised generators. This means that extra capacity can be added to the industry in small increments, which will reduce the risk of over-capacity and suppress competition. Gas is the preferred fuel because investment costs are lower, it is suitable for small stations and no anti-pollution equipment is needed.
New entrants to the electricity industry can be viewed on two scales.

- Small-scale generation (i.e. below $10MW_e$), which is becoming easier due to (i) changes in legislation and (ii) the higher generating efficiencies offered by the up-to-date Combined Cycle Gas-Turbine plant (CCGT), (iii) the market for small-scale CHP plant is growing with its local on-site generation of heat and electricity achieving even higher overall energy efficiencies and substantial economic savings when applied to appropriate applications.

- For large-scale electricity generation the barriers to entry are significantly higher and include (i) the provision of capital required for the substantial cost of building such systems and (ii) the current pollution restrictions which would make the construction of a coal-fired power station impossible today. There are also high exit costs for large generators and this is especially the case for nuclear-generated electricity with, as yet undetermined cost of decommissioning.

Other barriers to entry will be discussed briefly:

Licence: If generation is over 10 MW a licence is required from the industry's regulator (OFFER). For smaller generation capacity the regulations are more relaxed, which should encourage smaller new entrants into the market place. The obtaining of a licence can be a complex and lengthy task and may act as a barrier to entry.

Price: Access to electricity distribution channels has improved significantly. However, previously the unit price paid for exported electricity to the grid was insufficient to encourage the export of electricity from independent generators. The sale of electricity in these cases would improve their economic viability.

Geographical: Barriers to entry from generators which operate in countries outside England and Wales exist in the form of the construction of interconnecting links - the political will to install such links and the capital required. At present two inter-connectors are operational, these are the links from Scotland and France. A new link between Northern Ireland and Scotland will be completed later this year and should become operational shortly afterwards. Throughout Europe the transfer of electricity across political frontiers is becoming increasingly more common for large imports or exports.

Power of the buyers

The power of the buyers can be seen on two levels.

1. Buyers with demand for electricity above 100 kW (Non-franchise market). These relatively few buyers will have a choice of who to buy their electricity from with low switching costs. They are also demanding lower prices and increased levels of service and security of supply.
   The power of these buyers is **'high'**.

2. Buyers of electricity who require less than 100 kW (Franchise market) will have to buy from their local REC until 1998.
   The power of these buyers is **'low'**.

From April 1994 the market place offers more choice to consumers whose demand for electricity is above 100kW. Pre-1994 this choice was only available for consumers with a maximum demand of above 1MW. This change has brought a greater degree of competition to, the non-franchise market by allowing the larger consumers (above 100kW) to choose their supplier and, therefore, negotiate cheaper electricity prices. The change to the franchise boundary from 1MW to 100kW and the subsequent increase in the numbers of non-franchise customers has now split the total demand for electricity almost evenly between the two markets sectors. Response from suppliers and buyers in the industry to the changes in the franchise market were delayed while each sector determined how the new market would operate.

Power of the suppliers

Until 1998 the suppliers also fall into two categories:-

1. Above 100 kW - The power of these suppliers as determined by the author is **'low'**.

   The power of the suppliers of electricity in the UK is being slowly eroded as a consequence of the introduction of competition into this sector of the industry. Increasingly, the RECs are finding that local customers are buying their electricity either from other RECs, located in other parts of the country, or from one of the main generating companies. Electricity is a commodity and it is very straight-forward for customers to switch from one supplier to another. In addition, the technology connected with the on-site generation of electricity is becoming more reliable and cheaper as the market enlarges, thus giving consumers more choice.

2. Below 100 kW - The power of these suppliers as determined by the author is **'high'**

   Electricity is important to the buyers in this sector with few substitute products. The consumers cannot switch RECs, and consequently, there is usually only one potential supplier in this category if they do not generate their own power. Prices and service levels are monitored by the regulator (OFFER), which has been criticised for its inability to use its power to control prices.

Threat of substitutes

The threat of substitutes in 1997 is considered by the author to be **'low'** but rising. The reasons for this conclusion are described below.

The issue here is to what extent can any generator or supplier of electricity regard itself as operating in a discrete market, with a limited number of like competitors, as opposed to having a wider range of substitute products. The threat may come in one or more of the following:

Fuel switching: Mechanical-energy in the form of electricity is a 'high-grade' energy-source and cannot easily be substituted. However, some appliances which are currently electrically operated could be switched to alternative energy sources if adequate incentives were introduced. British Gas plc. introduced direct gas-fired domestic refrigeration units which could replace the more conventional electricity powered domestic systems, creating a switch from electricity to gas. The main drawback for these systems - which eventually caused them to be withdrawn from the domestic market - centred on the CO (carbon monoxide) emissions produced as a result of the combustion process, required for the operation of the gas-powered

refrigeration units. It took only a small number of accidents, caused as a result of carbon monoxide poisoning, for their commercial demise. Coal, gas or oil could be used in place of electrically-driven heating systems where they exist.
There has been a trend away from the use of lower grades of energy, which has resulted in lower average heat-to-power demand ratios. New hi-tech industries require high grade energy such as electricity to run the new systems. This change is mirrored in the domestic sector where the increased ownership of electrical appliances such as computers, microwave ovens, washing machines, tumble driers, dishwashers etc., has led to increased demand for electricity. Electricity competes directly with other fuels in space and water heating and cooking markets, which together account for 45% of domestic electricity consumption.

Energy-efficiency: Increasing the efficiency and the rate of uptake of domestic and industrial appliances will result in a reduced demand (all other factors remaining constant). Therefore, the increase of the energy-efficiency of appliances can be seen as a threat to the size of the market and consequently, the share of that market which each company might have.

Combined Heat-and-Power: CHP can produce heat and power at a higher overall efficiency. It would make an attractive substitute to electricity only generators where it can be used effectively.

Rivalry - Industry competition

Rivalry in the industry can be considered as **'medium'** and increasing as a result of the following:

- Electricity is a commodity and large customers - above 100kW - can easily switch supplier without incurring severe penalties.
- The number of generators in the industry has increased since privatisation, which is reducing the average capacity of competitors.
- Growth in the demand for electricity has slowed in recent years and the market is well supplied.
- Approximately 5.5% of the UK's electricity is imported. This could rise significantly in the future.
- High fixed costs in the past, however, these are decreasing as smaller plant enters the market.

When the final liberalisation of the electricity market is completed - which will occur in 1998 - it will be possible to purchase any amount of electricity from any licensed seller in the market place.

2.3.2 Analysing the Industry's Environment

Another step towards the development of useful forecasts of the future for the industry is achieved by analysing the pressure factors in the industry. These factors represent some of the influential forces acting either internally or externally upon the industry. The industry forces have been examined via the Five-Forces model [57], now the industry's strategic environment will be studied via the Social. Technological, Economic, Environmental and Political (S.T.E.E.P) analysis.

S.T.E.E.P. Trend Analysis

The S.T.E.E.P. analysis - outlined in Appendix A, highlights a large number of potential eventualities in the social, technological, economic, environmental and social worlds. These could (or will) have some influence on the UK ESI, which includes the CHP market. The most significant elements of this analysis as judged by the respondents to the questionnaire (see Appendix B) and the researcher are developed further. A summary of these factors when considering future changes to the industry's environment are presented below.

Technological

The concept of an unlimited and sustainable source of energy, emerging as a result of technological developments, is an attractive one. Unfortunately, this remains unlikely in the short-term and certainly within the time period defined for this study (i.e. 1997 $\rightarrow$ 2017AD). The best that might be expected is that the actual and perceived safety of the nuclear industry might be significantly increased through technological development. Another possible technical improvement could be achieved through the further increase of average generating efficiencies, which have been on the rise over the last decade. However, this increase has more to do with the removal of the aging coal-fired plants than advances in technology.

Environmental

Emission limits set for the industry - One of the results of the 1992 Earth Summit on climate control - which was held in Rio de Janeiro - was to set limits on the level of CO_2 emissions produced by each country. The aim was to return CO_2 emissions to 1990 levels (158 mtC or 579 mt CO_2 [58]) by the year 2000 AD. As a result the electricity industry was encouraged to reduce CO_2 emissions through the more-efficient and cleaner production of electricity. Following privatisation a program of removing older less-efficient and more-polluting generating plants from the industry was already being pursued. Thus, the steady increase of average generating efficiencies has led to a reduction in CO_2 emissions for each unit of electricity generated. The government confidently expects to exceed its target for CO_2 reduction by the year 2000 [59]. Furthermore, the new Labour government has indicated its desire to see the level of CO_2 reduced significantly beyond the levels already set (-20% of 1990 emissions by 2010). Dramatic measures (eg., a significant switch to nuclear electricity) would be required to achieve these new levels, which are unlikely to be unacceptable to the less enthusiastic governments such as the USA and Australia. More acceptable alternatives, such as CHP - with efficiencies of up to 90% - currently exist and could contribute towards further reductions if implemented on a wider scale.

	Year					
	1990	1991	1992	1993	1994	1995
CO_2, mtC	158	159	155	151	151	148

Table 2.3: CO2 emissions for the UK from 1990 to 1995 [21].

Economic

Carbon Tax: The introduction of a carbon based tax would have a direct effect on electricity prices, which in turn would reduce consumer demand and consequently CO_2 emissions. This effect was widely expected following the introduction of VAT on fuel in 1994, however, increased efficiencies achieved by the industry produced price reductions which largely offset the VAT increase. In the budget of 1997 VAT on domestic fuels was reduced from 8% to 5%.

Social

Apart from the increasing public concern for the environment - which will have an inescapable effect on the energy sector - general changes in the pattern of energy consumption brought about by the demand for more energy-efficient appliances or a move away from electrically-powered equipment, would account for the most likely social changes for the industry. Changes in attitude may develop as a result of increased levels of information or education concerning matters of energy efficiency in both the domestic and industrial sectors of the electricity industry.

Political

Change of government. The outcome of the 1997 general election brought about a change of Government from Conservative to Labour. Action from the new Government may involve:

1. Windfall-profit taxes on the industry to recoup what the Labour government regard as excessive profits as a result of undervalueing companies prior to privatisation. In the first Labour budget for about two decades, it was announced that a one-off 'windfall-tax' payment will be applied to a range of companies which were privatised by the previous government. These will include the electricity generators and suppliers. The tax will remove of £billions from the companies concerned, effecting both share-holders and employees. The share price of all the companies, expected to attract this

tax, declined in the first half of 1997 to compensate for the predicted loss of capital.

2. Margaret Beckett (President of the Board of Trade) announced that a wide ranging review would be undertaken concerning the role of the regulators in their associated industries. This will include a review of OFFER and is anticipated to insist on stricter regulation for the industry. Currently it is considered by the Government that the regulator is not paying enough attention to the views, interests or requirements of the consumers. The probable outcome will mean that future price increases made by the electricity industry - especially to the domestic sector - will be heavily restricted, together with senior managers and directors salaries. The industry will not be reverted to public ownership by the current Labour party.

3. The Labour Party's pre-election manifesto included an intention to reduce CO_2 emissions to 20% below 1990 levels by 2010 [60]. The deputy prime minister, John Prescott, recently reiterated these statements and also stated that

   > We must also make major efforts to accelerate progress in the UK on energy-efficiency, CHP, renewable energy and promote conservation. We strongly supported Combined Heat-and-Power in opposition and in government we will positively promote it [60].

   If these words are translated into action then the industry will have to change and the CHP sector is likely to benefit from these changes.

2.4 Forecasting changes to the industry: Future Scenario Analysis

The expansion of electrical capacity requires a high level of investment and long lead times for construction and installation. Consequently, long-term strategy formulation is vital if companies are to position themselves correctly in future markets to reduce risks. The previous section analysed the structure of the ESI by examining the industry's environment and the level of competition within it. Using these key factors, which emerged as a result of the Five-Forces, S.T.E.E.P. analysis together with results from the questionnaire, five possible scenarios have been developed. Scenarios are realistic descriptions of possible future states of the electricity industry's environment. It is usual and most beneficial to construct more than one scenario so that strategies can be tested against a wide range of possible futures. Scenarios can be used to explain potential future industry developments and to identify the interaction of uncertain future trends and events, particularly 'casual' relationships and key decision-points.

2.4.1 Scenario Analysis

The five scenarios, which have been selected for analysis are:

1: **New and reduced CO_2 limits set by the Climate Control Conference + stricter environmental legislation.**

2: **Changes to the Pool mechanism for pricing electricity.**

3: **Business as usual - Change to the electricity franchise market in 1998 - Change of UK Government as of May 1997**

4: **Development of clean abundant fuel source.**

5: **Unlimited potential imports to the UK market of internationally traded electricity.**

The factors which relate to the construction of these five scenarios are described for each scenario separately on the following five pages. The effect on the ESI and the CHP market which would be caused by each of the five scenarios will be predicted to the year 2017. Several management tools together with the scenario analysis model (see Figure 2.5, 2.6 and 2.7) will be utilised. Figure 2.9 presents a summary of the impact on three 'key features' in the market - demand, costs and competition. These predictions were achieved with the aid of responses given by individual specialists and the author's analysis to the questionnaire. Each of the scenarios are now examined in order to determine their effect on the 'key features' in the electricity market. Consequently, the results can be viewed as partially subjective as strict objectivity is not possible in this type of study.

SCENARIO 1:

1. Pressure Factors ($\mathbf{PF}_j$):

   - Increasing links made between high pollution levels and bad health.
   - Cross border pollution reaches unacceptable levels.
   - International opinion regards reduction of CO_2 emissions as a priority.
   - European opinion dictates that levels of pollution are reduced.
   - Environmental pressure groups succeed in persuading governments to take some form of action over pollution.
   - More specific apportioning of emissions to the energy source

2. Scenarios ($\mathbf{S}_i$)

   - Emission control measures are implemented in order to reduce CO_2 and other pollutants.

3. Likelihood ($\mathbf{L}_i$): **of scenario developing: 80% to 90%**

4. Outcome Factors ($\mathbf{F}_n$):

   - Higher unit electricity prices to provide an incentive for energy conservation.
   - A sliding scale of higher electricity prices depending on the fuel input and the efficiency of production for electricity.
   - Positive incentives for energy-conservation and the implementation of energy-efficient and less polluting technologies.
   - The promotion of related education and information on energy conservation.
   - Positive incentives for cleaner energy-producing technologies.
   - The phased removal of nuclear power from the electricity industry.

5. Effect ($\mathbf{E}_f$):

   - Higher unit electricity prices will favour CHP if all other relevant factors remain the same.
   - Positive incentives to promote energy-efficiency and better utilisation of energy will aid CHP.
   - Promotion of the benefits of CHP will benefit the industry.

6. Collective effect on the CHP market (CE_{CHP})

   - The strategic impact is estimated at approximately 3.75 (high) - see Figure 2.10. This scenario has a high probability and falls within the critical impact region in the figure. Therefore, it will be considered further.

SCENARIO 2:

1. Pressure Factors ($\mathbf{PF}_j$):
   - Pressure building from large consumers to change the way electricity prices are determined.
   - Criticism from electricity companies [61].
   - The current pool systems allows all generators to be paid at the marginal price bid into the pool, giving the lowest cost generators large profit margins for electricity which is being sold at a significant margin above cost. This system supports the higher cost producers.
2. Scenarios ($\mathbf{S}_i$)
   - Change to the Pool pricing mechanism.
3. Likelihood ($\mathbf{L}_i$): 60% likely
4. Factors ($\mathbf{F}_n$):
   - If the current system for pricing electricity is altered it is most likely to move to a more free market. Under these circumstances the lower cost producers will be able to sell to large customers at a reduced price. This will put pressure on all generators as the price reductions and cut in profit margins due to increased competitiveness filters through the generation and supply system. The highest cost producers - such as the coal-fired generators - will be the first to feel the pressure to cut their operating costs.
   - Large users of electricity will have a greater degree of choice from whom their electricity is purchased and at what price.
5. Effect ($\mathbf{E}_f$):
   - If the changes to the pool pricing system lead to a more open market for the pricing of electricity then unit electricity prices will fall across the entire industrial market. This won't help CHP, which requires high electricity unit rates in order for it to stay economically attractive (all other factors remaining constant).
6. Collective effect on the CHP market (CE_{CHP})
   - The downward pressure on electricity prices will significantly reduce the economic attractiveness of CHP. The results from the questionnaire indicates a strategic impact of 2.75 (medium) - see Figure 2.10. The probability of this scenario is high and falling within the critical impact region in the figure and it will be considered in more detail.

SCENARIO 3:

1. Pressure Factors ($\mathbf{PF}_j$): **None.**
2. Scenarios ($\mathbf{S}_i$): **Business as usual.**
3. Likelihood ($\mathbf{L}_i$): **100%**
4. Factors ($\mathbf{F}_n$):
   - Windfall taxes on the utility companies, will in-part be transferred to the consumer via higher electricity and gas prices.
   - A greater degree of regulation through OFFER - Labour Government have stated their intention to review the role of OFFER. They believe that not enough has been done with regards to price controls and that the electricity companies produce unnecessarily large profits. Consumer interests will be given priority (A green paper is due in Jan 1998).
   - An increased target might be set for CHP (to 10.000 MW of installed capacity) as stated in a previous Labour memo [62].
   - Reduction of VAT on domestic fuels from 8% to 5%.
   - Liberalisation of the electricity franchise market in 1998.
5. Effect ($\mathbf{E}_f$):
   - Higher electricity prices will benefit CHP uptake if all other factors remain constant. It is likely, under these circumstances, that an increase in gas prices may arise but the net effect will still be beneficial for CHP since electricity prices have a greater effect on its economics than gas prices.
   - Increased regulation is very probable and could take many different forms. It is most likely to occur as price capping which would not benefit CHP economics.
   - Increasing the target for installed CHP capacity will be favourable for the CHP market as the Government is likely to introduce supporting measures to ensure that the target is met.
   - The reduction or removal of VAT will only benefit the domestic sector: The CHP market is unlikely to profit from this measure as currently it is mainly used by the industrial sector.
   - Liberalisation of the franchise market will result in a more free-market for electricity. However, this is not expected to effect the CHP market significantly.
6. Collective effect (CE_{CHP}):
   - Strategic impact has been determined at 2.5 (medium) with a favourable effect on CHP use. This scenario falls within the critical impact region in the figure and will be considered further.

SCENARIO 4:

1. Pressure Factors ($\mathbf{PF}_j$):

   - Continued research into environmentally less polluting and more energy-efficient energy production.
   - Increasing public and international pressure to make the nuclear industry safer. This might be achieved by improving methods for the disposal of nuclear waste and the reduction or elimination of the risk associated with nuclear generated electricity.

2. Scenarios ($\mathbf{S}_i$)

   - Development of a clean, safe and abundant fuel source.

3. Likelihood ($\mathbf{L}_i$):

   - 34%

4. Factors which will be affected if the scenario develops ($\mathbf{F}_n$).

   - Pressure will increase to reduce generating costs and efficiencies leading to the removal of most of the high cost and highly polluting generators from the industry.
   - Large users of electricity will have a greater degree of choice about where they buy their electricity and at what price.

5. Effect ($\mathbf{E}_f$):

   - The addition of large quantities of electricity to the market will result in a reduction of electricity prices disadvantaging CHP.
   - The new sources of electricity will be produced without significant levels of pollution. As the achievement of reduced emission levels through the more efficient production of energy is a major influence to the attractiveness of CHP to the environmentally conscience, any superior alternatives will diminish its appeal.

6. Collective effect (CE_{CHP}):

   - The downward pressure on electricity prices and the removal of the low emissions advantage of CHP will significantly reduce the economic and environmental attractiveness of the technology. The results from the questionnaire indicate a strategic impact of 2.75 (medium) - see Figure 2.10. This scenario falls outside the critical impact region and is not considered further.

SCENARIO 5:

1. Pressure Factors ($\mathbf{PF}_j$):
   - More inter-connectors between European countries are being constructed each year.
   - Trade in electricity between European countries is increasing.
   - Over capacity in some countries, therefore, electricity can be exported at below cost to undercut the home market.
2. Scenarios ($\mathbf{S}_i$)
   - Unlimited potential import of electricity to the UK market.
3. Likelihood ($\mathbf{L}_i$):
   - 32%
4. Factors ($\mathbf{F}_n$):
   - Downward pressure on electricity prices in the UK
   - Increased competition in the UK market
   - Reduction in the UK workforce in the industry.
5. Effect ($\mathbf{E}_f$):
   - Reducing electricity prices will not help the economic prospects for CHP.
6. Collective effect (CE_{CHP}):
   - The downward pressure on electricity prices will significantly reduce the economic attractiveness of CHP. The results from the questionnaire indicate a strategic impact of 2.00 (low) - see Figure 2.10. This scenario falls outside the critical impact region and it is not considered necessary to be considered further.

2.4.2 Analysis, Observations and Comments

The five scenarios have been developed and their effect on the various elements of the industry examined. The objective now is to highlight which of the elements involved in the development of the scenarios will be significant for the CHP sector.

The relative effect on demand (A), costs (B) and competition (C) for each scenario are analysed and plotted in the table shown in Figure 2.9.
The elements of the matrix are completed with one of three alternatives:

- No change - indicating that the effect of the scenario will have no effect.
- Up - indicating that the effect of this scenario will be to increase this factor
- Down - indicating that the effect of this scenario will be to decrease this factor

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
A Demand	NO CHANGE	DOWN	NO CHANGE	NO CHANGE	NO CHANGE
B Costs	UP	DOWN	NO CHANGE	DOWN	DOWN
C Competition	NO CHANGE	UP	UP	UP	UP

Figure 2.9: Impact analysis: Derived from a combination of the results from the questionnaire and the authors own views.

From the results produced by the questionnaire it has already been established that the level of electricity prices is a vital detail for the financial viability of CHP systems. Increased levels of competition resulting in lower electricity prices will be negative for CHP. In consideration of this fact and the results in Figure 2.9 scenario 1 appears to provide a positive future for the CHP market in the UK as costs are predicted to rise with the level of competition remaining the same as in 1997.

Strategic Impact Analysis

Figure 2.10 shows the basis for the selection of the three most appropriate scenarios. The management technique used to produce this figure are documented in references [63] and [64]. The strategic impact of scenarios 4 and 5 were predicted to fall outside the critical region and they will not be selected for further study.

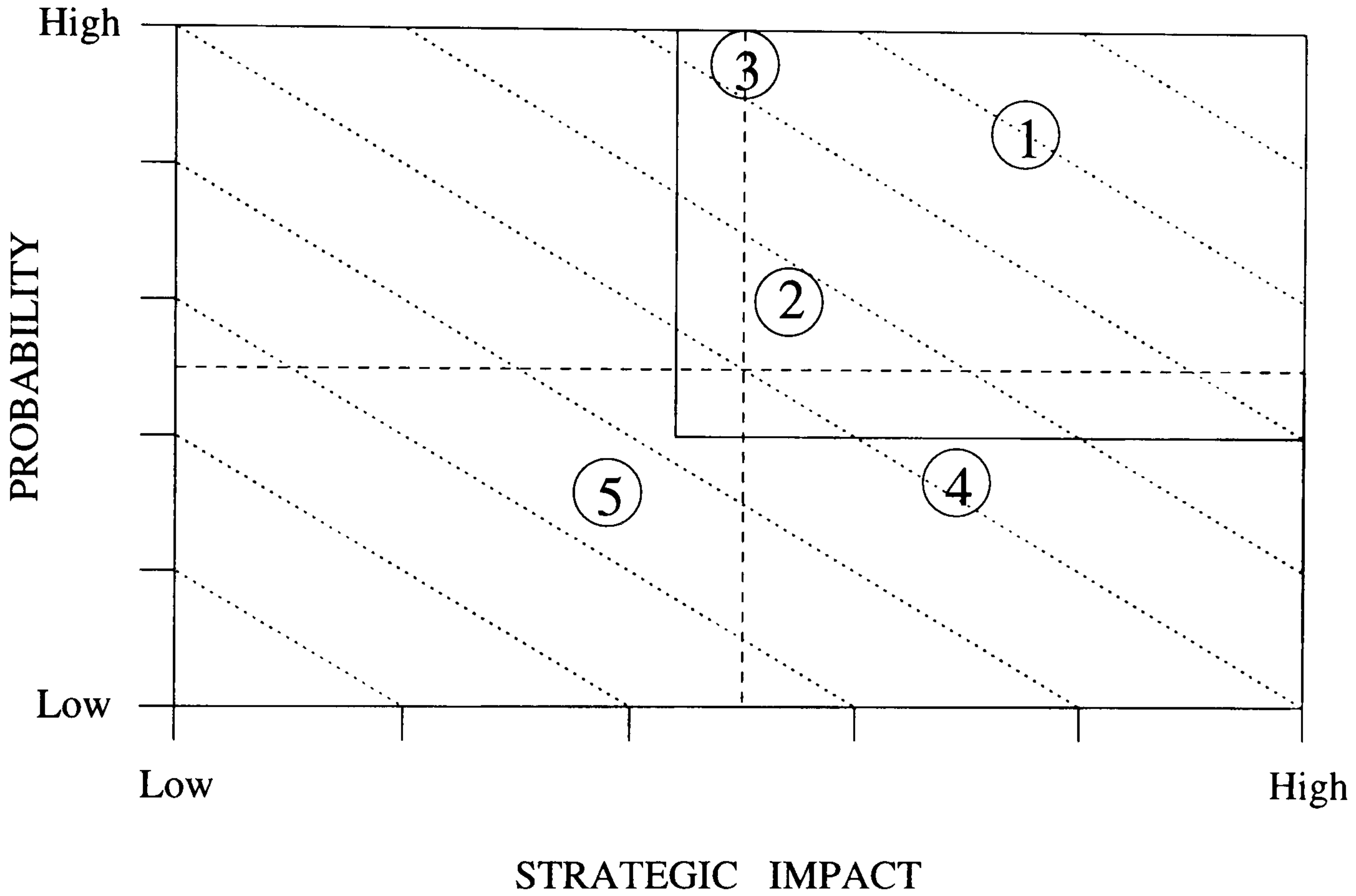


Figure 2.10: Strategic impact and probability diagram.

From Figure 2.10 it can be seen that scenario 1 (reduced CO_2 limits + increased pollution control) produces the greatest impression with regard to probability and strategic impact. The implications for the CHP market of the realisation of this scenario are positive and indicate an expansion of the market. Two important points underline this (i) the consistent increase of electricity prices, which improve CHP economics (all other factors constant) and (ii) any increase of the restriction for CO_2 emissions will put pressure on the UK Government to reduce emissions further. Improving energy-utilisation - via the adoption of CHP systems - provides an immediate means to achieving this goal. Therefore, an increase to the government-set target for installed CHP capacity is likely, as occurred following the last 'Earth Summit'. Additionally, the government may move to support CHP more actively through the supply of tax incentives or capital grants. The size of the CHP market would be expected to increase more rapidly as a result of this scenario.

The second most significant of the three scenarios is 'business as usual'. The most important feature to note is that historical events in the industry will be little help when making predictions about the future. This is because the industry is very dynamic with many significant changes - such as the new Labour Government and the liberalisation of the franchise market - either ongoing or planned. The new government has expressed support for energy-efficiency and specifically CHP. If this verbal support is translated into action in the shape of financial grants and favourable regulatory changes, then CHP will benefit. The final stage of the liberalisation of the electricity market in 1998 should lead to increased competition and a downward pressure on electricity prices. On balance, it is predicted that the CHP market will increase under this scenario but not as rapidly as in the case of scenario 1.

Changes to the pool pricing mechanism could have a significant effect on CHP if it leads to substantial decrease in electricity prices in all sectors of the electricity industry. Initially, large consumers will be the first to benefit by purchasing and negotiating the rate directly with the generator and by-passing the pool pricing mechanism. This will put pressure on other generators to cut prices and deal directly with consumers. Ultimately the effect will reduce profitability and lead to the highest-cost producers being forced from that part of the competitive market. The overall effect is likely to be a reduction of average generating-costs and downward pressure on electricity-prices in all market sectors. At best this will be neutral for CHP and more likely adverse, leading to a slowing of the expansion of the market as cost savings decrease when compared to the alternatives.

Industry forces revisited for the year 2017.

Following the strategic impact and probability analysis, summarised in Figure 2.10, the five original scenarios have now been reduced to three for the final analysis. For each of the three scenarios, which have been selected for their significance, the competitive forces for 2017 have been predicted - see Figures 2.11, 2.12 and 2.13.

Scenario 1: New and reduced CO_2 limits set by climate control conference + stricter environmental legislation.

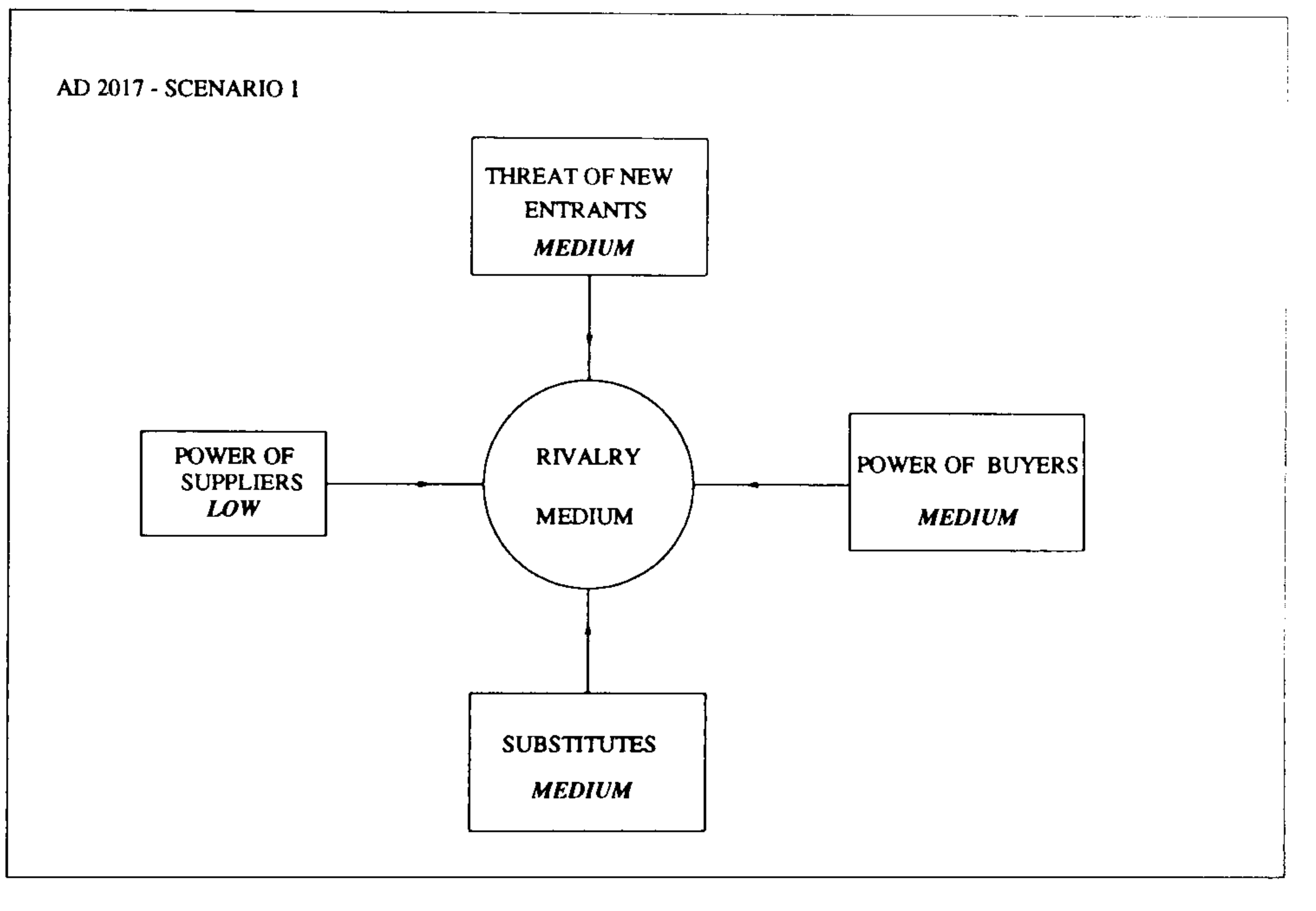


Figure 2.11: The industry's competitive forces in 2017 as a result of scenario 1.

According to each of the three scenarios the level of competition will be greater than it is at present. It is likely that this will drive the average level of electricity prices down. The possibility of new entrants moving in to supply the market seems at a similar level as in 1997. However, the threat of substitution has increased leading to even greater competition.

Scenario 2: Changes to the pool mechanism for pricing electricity.

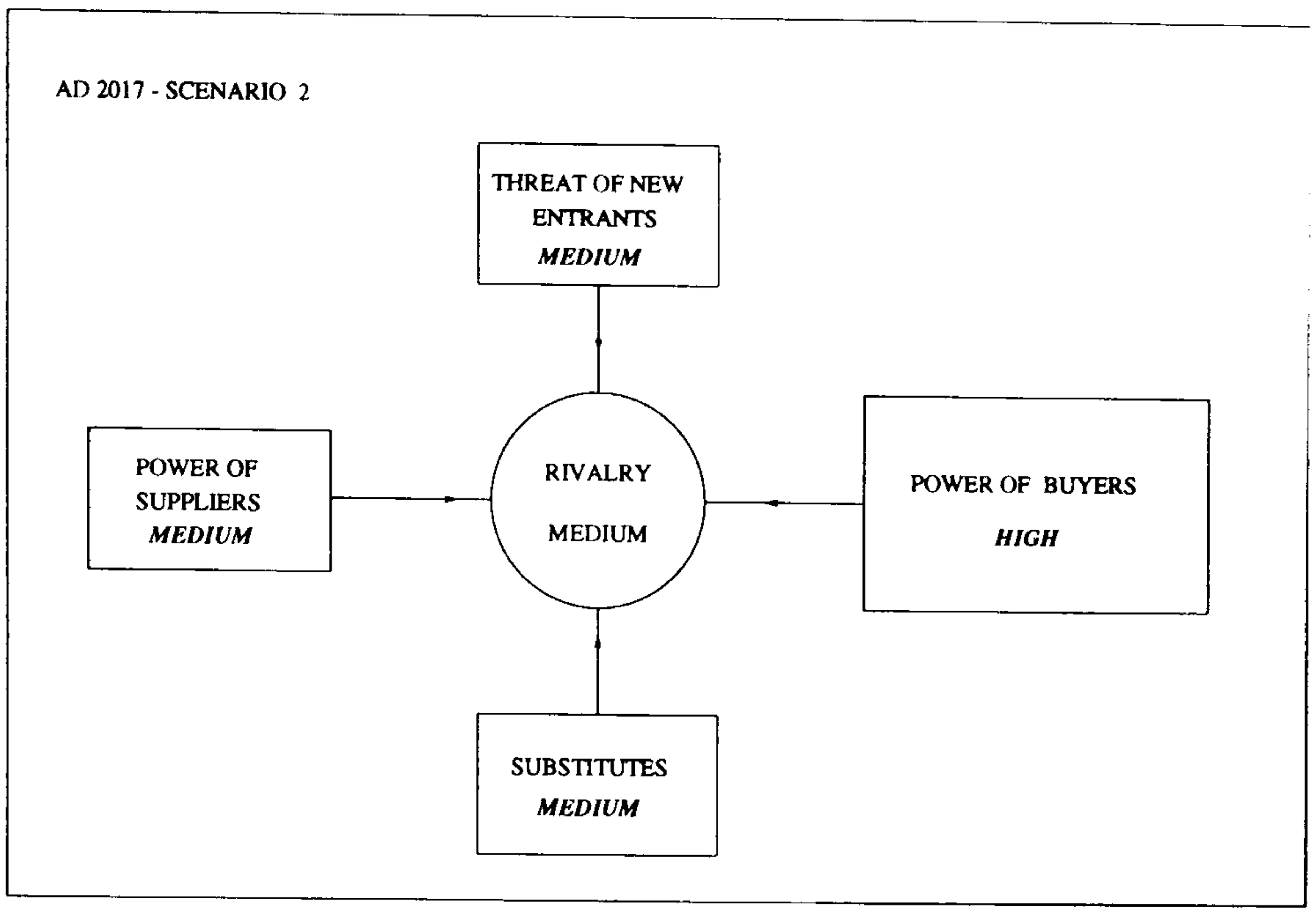


Figure 2.12: The industry's competitive forces in 2017 as a result of scenario 2.

Scenario 3: Business as usual

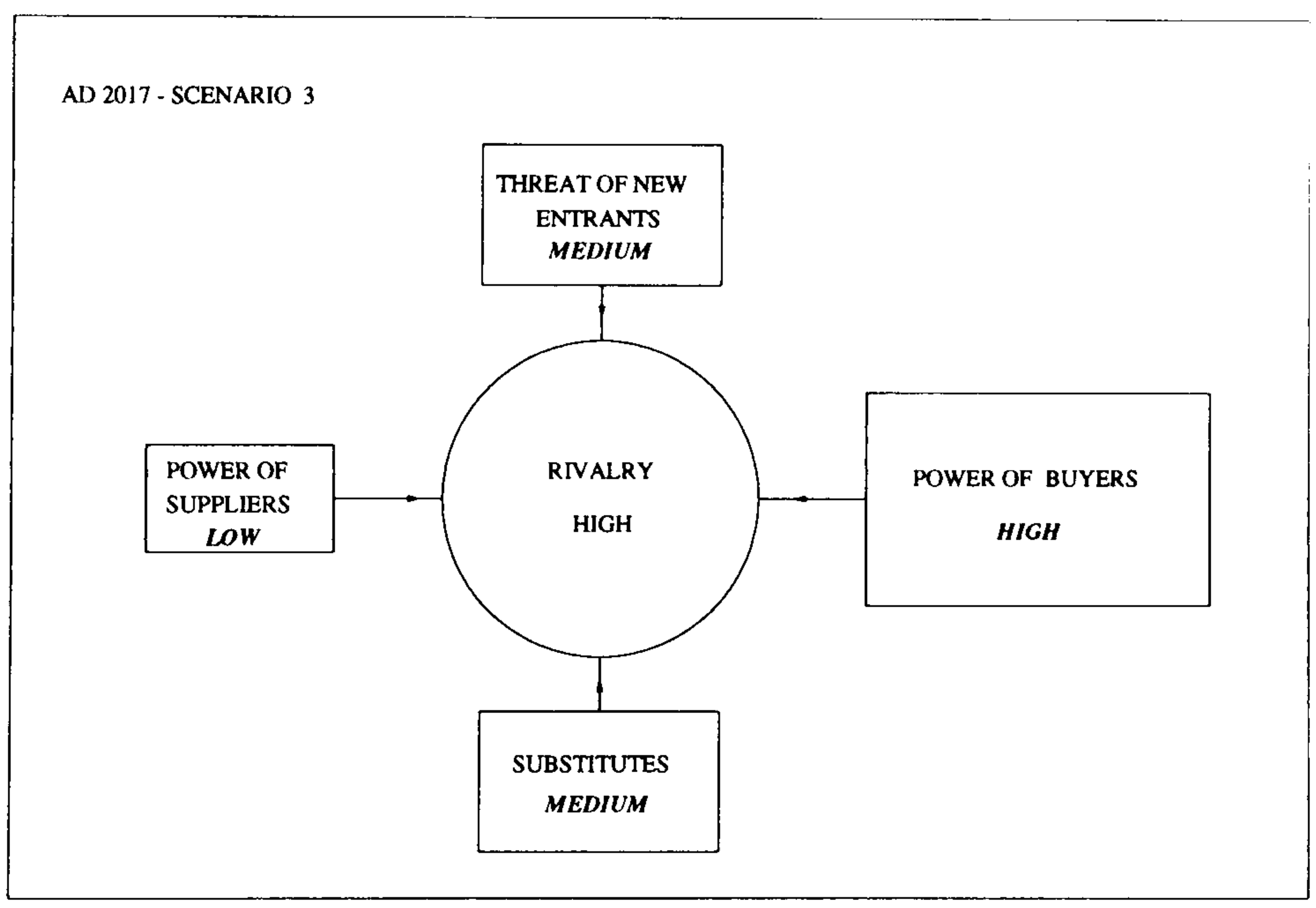


Figure 2.13: The industry's competitive forces in 2017 as a result of scenario 3.

2.5 Proposals for future work

This study has examined the electricity and CHP sectors in detail. A new management approach has been adopted wherever possible, utilising tools such as S.T.E.E.P. analysis, the five forces model and scenario planning. In order to extend the research one step further and to introduce an increased measure of objectivity the views of industry experts were solicited via a survey. The results of this survey were useful to this study, providing a degree of objectivity. The limitation of the work concerned the sample size, which was limited to 14 with a response rate of approximately 60%. Future work should seek to increase the size of the sample and widened the sample of experts to include more CHP users. Additionally it would be beneficial to incorporate new questions which examine the scope for CHP from the end-users point of view.

2.6 Conclusions and the implications for CHP

The last decade has seen dramatic changes to the UK Electricity Supply Industry. By 1998 the industry will have been transformed, in less than a decade, from a state owned monopoly to an open market for suppliers and consumers alike. The rapidity of this change has left a number of anomalies in the market place, which either favour or disadvantage particular elements of the industry. The industry is still in a state of change, which makes future predictions about its development difficult. It is highly likely that 20 years from now the structure of the ESI will be significantly different from the way it looks in 1997. Any of the many technological, economic, environmental, social or political developments in the ESI's strategic environment might cause this change. In order to present three plausible views of the future state of the industry and the implications for the CHP market, a study of the ESI's strategic environment, competitive forces and underlying trends has been undertaken. One certainty about the next 20 years is that the UK economy will continue to require energy to satisfy the needs of its citizens, but what will the environmental cost for this energy be? The technologies - such as CHP and renewables - exist to significantly reduce this cost. However, there exists many obstacles to the full integration of these systems into 1997's dynamic and free-market electricity industry.

The electricity generated by CHP accounts for approximately 6% of the UK's total sales. The future for CHP is inextricably tied to the future of the electricity industry as a whole. In conclusion, it seems likely that several elements from each of the three scenarios will become reality. The overall future for CHP if scenarios 1 and 3 result is positive with a strong emphasis on energy-efficiency, reform of the role of the regulator, the increasing of the Government-set target for installed CHP capacity (10 GW by 2010 and 13GW by 2017), the implementation of a carbon based tax and the removal of restrictive (anti-CHP) legislation. The realisation of scenario 2 will put strong downward pressure on electricity prices, which in isolation will adversely effect the economics of CHP systems. Respondents to the questionnaire put the following factors as most significant for the continuing growth of the CHP market:

1. Higher electricity prices.
2. A reduction in the capital costs of CHP units.
3. A more open market for the import/export of electricity.
4. Government backing and incentives for the CHP industry.
5. Jointly - Cheaper gas prices and the removal of any remaining 'unfair' regulatory, licensing or legislative barriers for CHP within the electricity industry.

Above all the future for CHP requires a supportive Government; if this technology is left only to the peculiarities of market forces, generally the lowest cost and quickest return options will be selected without any concern for the long-term and wider environmental effects.

Implications of the findings in Chapter 2 for the rest of the research.

Five significant factors for the development of the CHP sector were identified. Of these, only the reduction of capital costs of CHP plant falls wholly within the control of CHP manufacturers. The other four, headed by the cost of electricity are either market dictated or controlled by one form of governing body. Because of the wide fluctuations of electricity and gas unit-prices over time it is difficult to measure the benefits brought about by the application of CHP in monetary and pay-back terms alone, as these too will vary constantly. This can result in CHP being the option for today but not tomorrow or vice versa. One of the major consistent factors of the appropriate use of CHP is that energy consumption and consequently polluting emissions will be reduced. Therefore, wherever possible throughout the rest of this thesis the benefits of CHP will be expressed in terms of energy saved in kW and kg of CO_2 displaced.

Chapter 3

Combined Heat-and-Power

Introduction

Chapter 3 begins with an overview of the process of power generation in the UK and proceeds by identifying the inefficiencies of centrally-generated electricity produced from fossil-fuels. This provides the background for the introduction to the technology of combined heat-and-power (CHP), which offers a more energy efficient alternative to separate heat and electricity production. A comprehensive review of the available CHP systems is presented together with a detailed description of the relevant environmental, economic and political factors, which are critical for the successful application of this technology. Finally, the CHP market is analysed in order to complete the full structure of the industry. The background is thus set for the main body of new research which is presented in Chapters 4,5 and 6.

3.1 Conventional Electricity Generation

Electricity is the purest and most convenient form of energy, and is capable of being converted to other energy forms with up to 100% efficiency (see Figure 3.1) [65]. Its greatest advantage is the ease with which the energy can be transported to the point of demand, yet for many purposes, such flexibility is rarely needed. More than 80% of the UK's supply of electricity - which amounted to 310 TWh in 1995 [3] - is produced from the combustion of fossil-fuels in a relatively small number of centrally located generating stations. This centralised form of electricity production is extremely wasteful and leads to inefficiencies when the full *fuel* $\rightarrow$ *heat* $\rightarrow$ *mechanical energy* $\rightarrow$ *electrical energy* $\rightarrow$ *distribution* $\rightarrow$ *consumption* chain is analysed. The other 20% (approximately) is produced by nuclear power, on-site generation, renewables, biofuel combustion or imported from Europe. The usual efficiencies of scale, which can be applied to large-scale centralised generation, are negated in the main by the thermal and distribution losses: the most inefficient link in the chain is the conversion process of heat to mechanical energy.

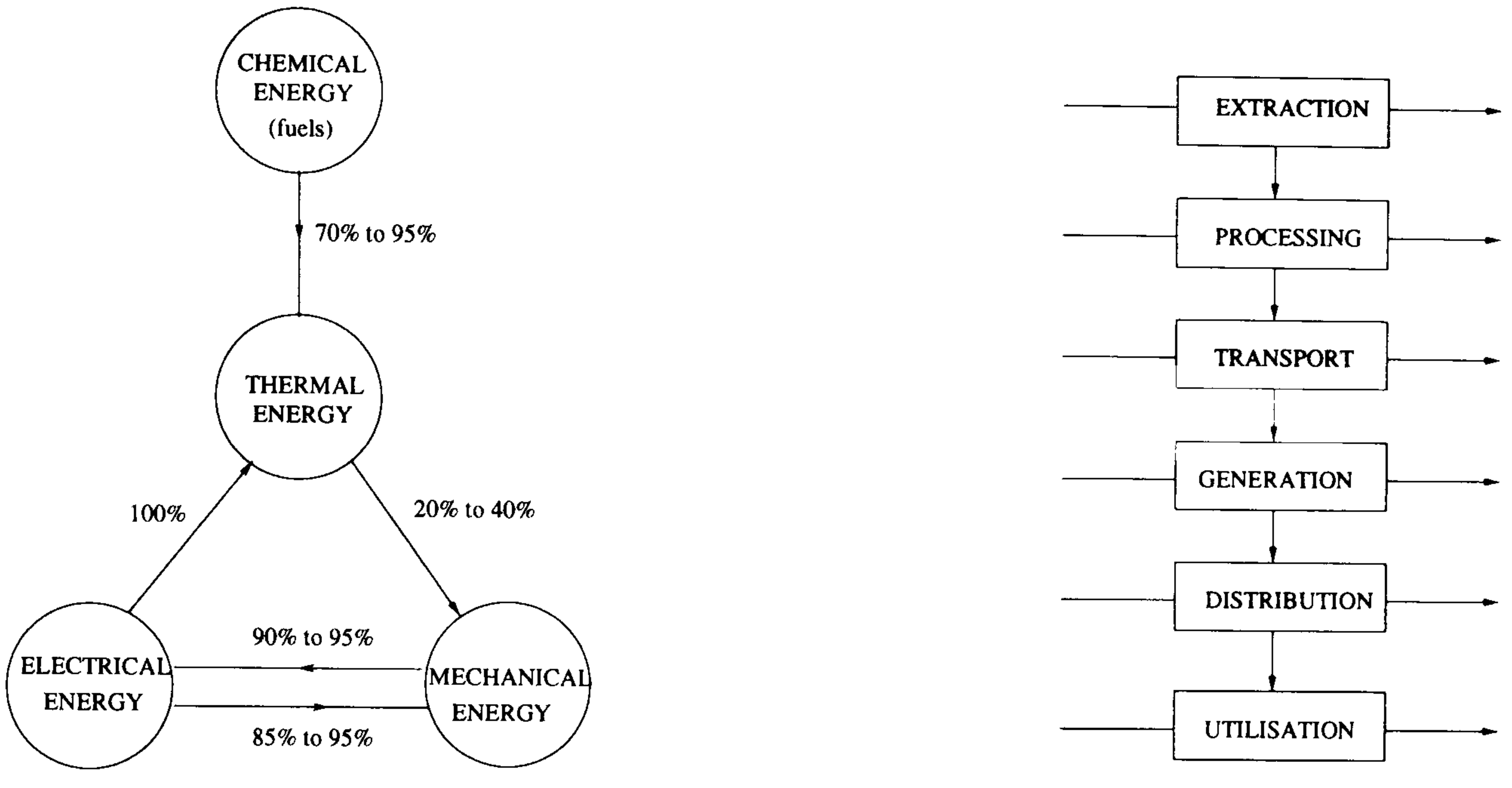


Figure 3.1: Energy conversion diagram [4], [5].

3.1.1 Thermal Efficiency of Electricity Generation

If electricity is generated using an heat-engine, then only a finite proportion of the input chemical-energy can be converted to electrical power. The remaining energy is rejected as heat. This is an inescapable thermodynamic fact. At power-only stations, the rejected heat is discharged into the atmosphere via cooling towers, an adjacent river or the sea. This will mean that on average little more than 35% of the initial *gross* calorific value of the primary-fuel is converted into useful energy [9]. Wide-scale production of energy in this way is extremely wasteful and arises as a consequence of the following thermodynamic laws:

- First Law: To produce work a quantity of heat must be supplied to an engine.
- Second Law: To produce work not only must a quantity of heat be supplied to an engine but a proportion of that heat has to be rejected, at a lower temperature than that at which it was supplied.

The consequence of the first law is that energy is always conserved (except where nuclear reactions are concerned). The consequence of the second law, however, is that a heat engine can never be 100% efficient in the conversion of heat into work. The theoretical maximum efficiency of all heat engines is determined by the difference between the temperature at which input heat is available and the temperature at which heat can be rejected. The maximum possible theoretical efficiency of a heat engine - which cannot be realised in practice - is defined as the 'Carnot Efficiency'

$$Carnot\ Efficiency = \frac{T_{IN} - T_{OUT}}{T_{IN}}$$

T_{IN} = Maximum temperature of input heat in degrees Kelvin.
T_{OUT} = Minimum temperature of heat rejected in degrees Kelvin.

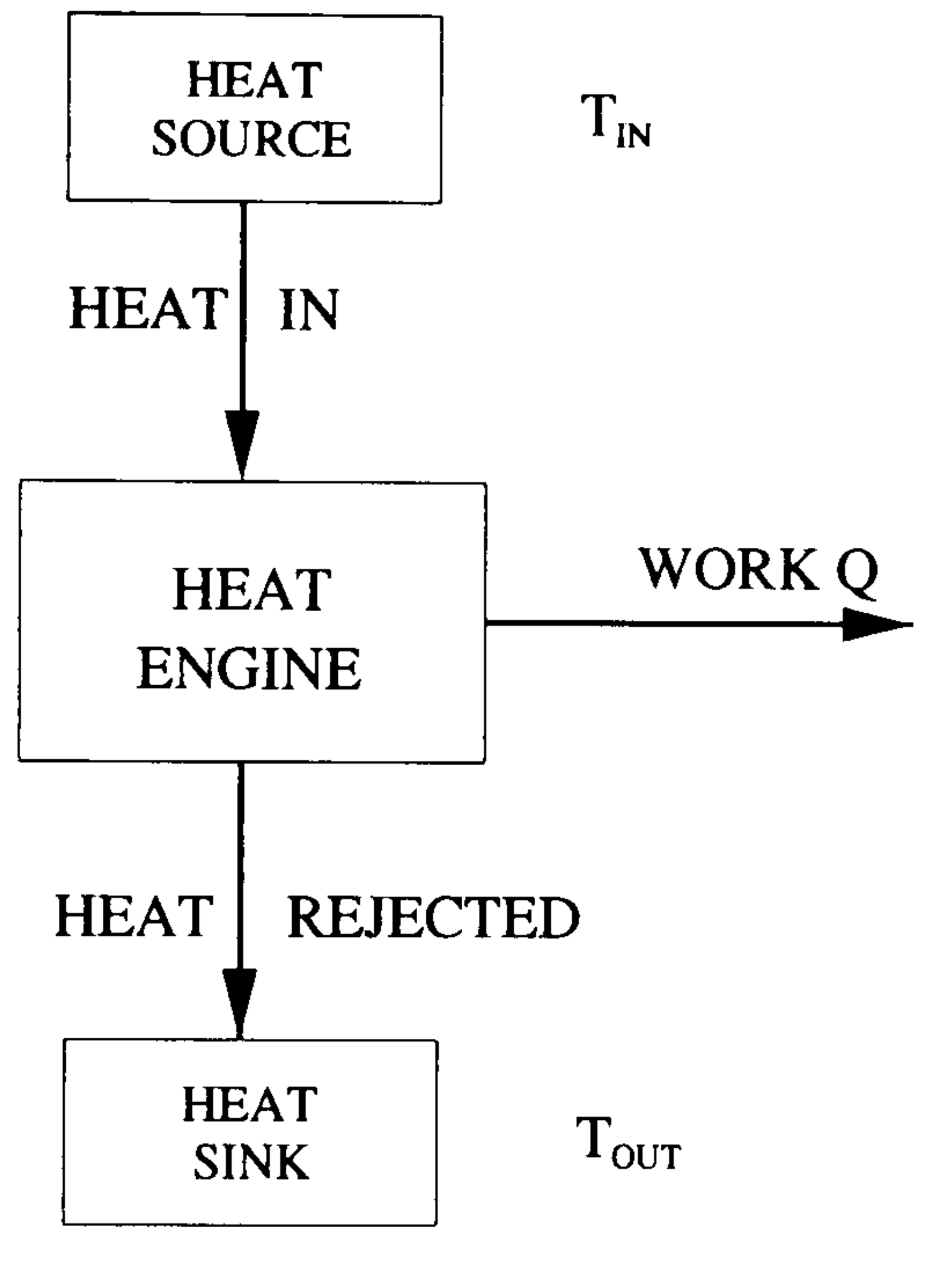


Figure 3.2: The heat engine.

In practice T_{IN} represents the maximum fluid -temperature achieved inside the heat engine, T_{OUT} is limited by the lowest exhaust-temperatures available.
The highest generating-efficiencies are obtained from combined-cycle gas-turbines (CCGT) (with no heat output), where the use of steam turbines can raise the overall operating efficiency from 35% to a maximum of about 50% [23].

3.1.2 Transmission and Distribution Losses (T & D)

In addition to the thermal losses associated with the production of electricity, transmission losses must also be considered. These losses in 1995 amounted to 7.5% [66], a reduction from 9% in 1990 [67], and are incurred when the electricity is generated centrally, and therefore, requiring transmission across large distances

	(%)	
Fuel Used	1992	1996
Coal	64.5	43.5
Nuclear	24.5	29
Gas	1.4	21
Oil	7	4
Hydro	0.5	0.3
Other Fuels	0.1	0.2
Imports	2	2

Table 3.1: Fuels used in electricity generation, energy supplied basis [3].

in order that the electricity can be supplied to the the end user. About one-fifth of this is due to magnetisation losses (in the transformers) and which are independent of load. The greatest proportion of the transmission and distribution losses occur as resistance losses (in the form of heat) in cables, and will vary with the square of the current used. A consequence of this is that the proportion of power lost for a marginal unit of load will be double the average rate. T & D losses lead to the need for the production of more centrally-generated electricity than is actually required locally by the end-user.

3.1.3 Generating Efficiency Improvements in the Industry

The average generating efficiency for UK power stations has been increasing in recent years. The main reasons for the improvements are; i) the removal of old coal-fired power stations from the system and ii) the inclusion of more higher efficiency CCGT plant to replace the old stations.

3.2 Combined Heat-and-Power: An Introduction

Combined Heat-and-Power (CHP) is the term used to describe the simultaneous production and use of heat - usually in the form of hot-water or steam - and power - usually in the form of electricity. CHP plants can convert more than 80% (and even 90% in some cases where additional heat recovery equipment has been installed) of the primary fuel input into usable energy and therefore, offers an more energy-efficient alternative to separate heat and power production where the electricity is generated centrally and the heat is produced locally in on-site boilers (see Figure 3.3).

CHP basically means that the waste heat from the production of electricity or mechanical power - which is rejected into the environment during large-scale central

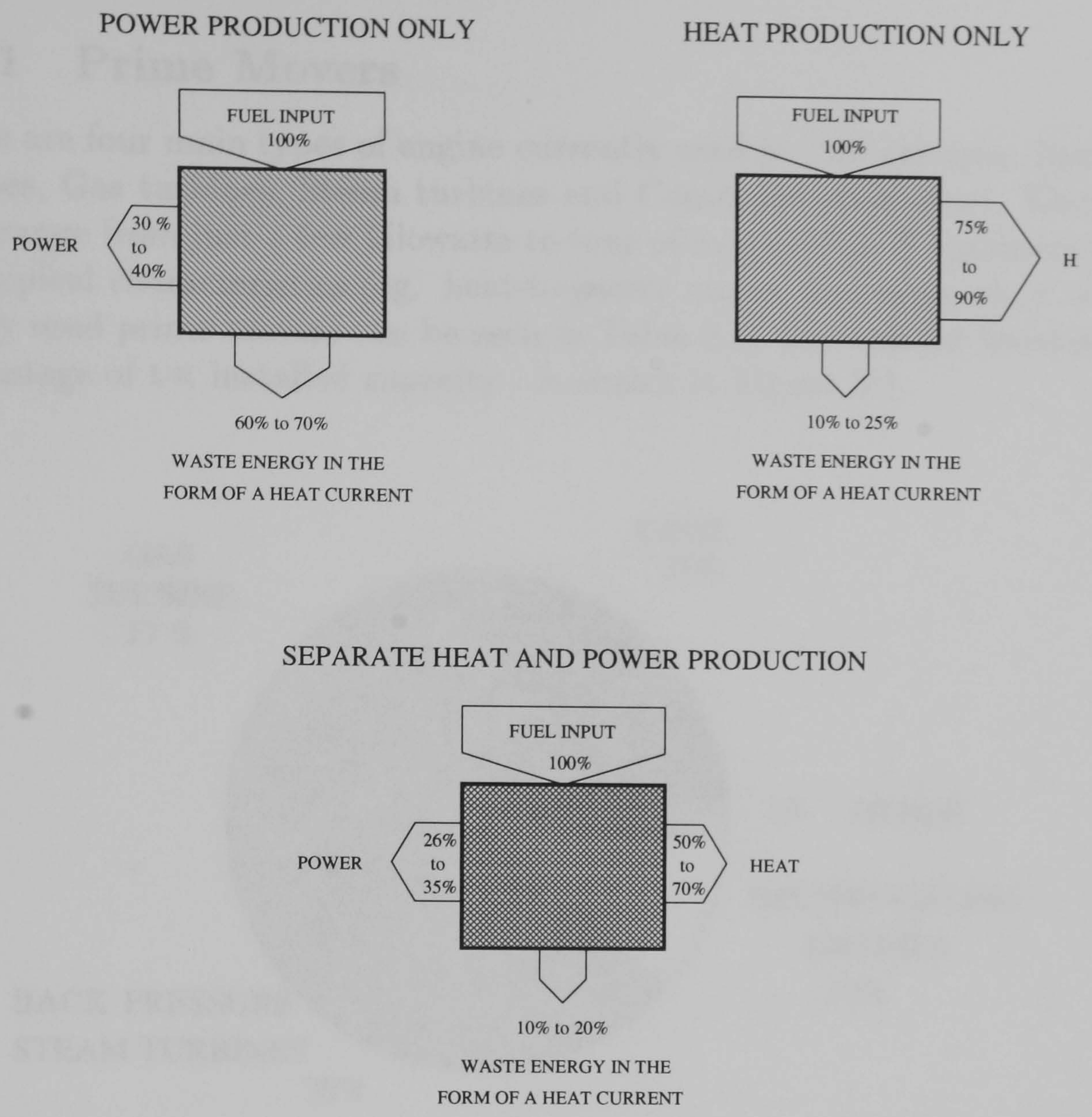


Figure 3.3: The efficiency benefits of CHP vs. conventional heat and power production.

generation - is utilised in some process demanding a low to medium temperature heat source. This heat can be the exhaust from an internal-combustion engine or turbine power plant or the low pressure steam exhaust from a turbine. CHP units will produce less electricity for the same fuel input than power only stations because they are required to reject heat at a higher temperature. The term CHP is synonymous with co-generation or total energy often used in the European Community, the United States and other parts of the world where the technology is widely used. CHP is one of the oldest forms of electricity generation and has been used in industrial applications in the UK since the last century [68]. CHP can be viewed on three different scales; micro-scale (below 15kW$_e$), small-scale (15kW$_e$ to 1MW$_e$) and large-scale (above 1MW$_e$), however, these size ranges are not definitive across the industry and variations can be observed frequently, especially in the definitions of small and large-scale applications. Utility companies, for example, might view large-scale CHP as above 5-10 MW$_e$.

3.2.1 Prime Movers

There are four main types of engine currently used in CHP systems: Reciprocating engines, Gas turbines, Steam turbines and Combined cycle plant. Electrical outputs range from just a few kilowatts to tens of megawatts. A summary of some of the typical characteristics (eg. heat-to-power ratios, fuel type, etc.) of the commonly used prime movers can be seen in Table 3.2. The market breakdown - as a percentage of UK installed capacity - is shown in Figure 3.4.

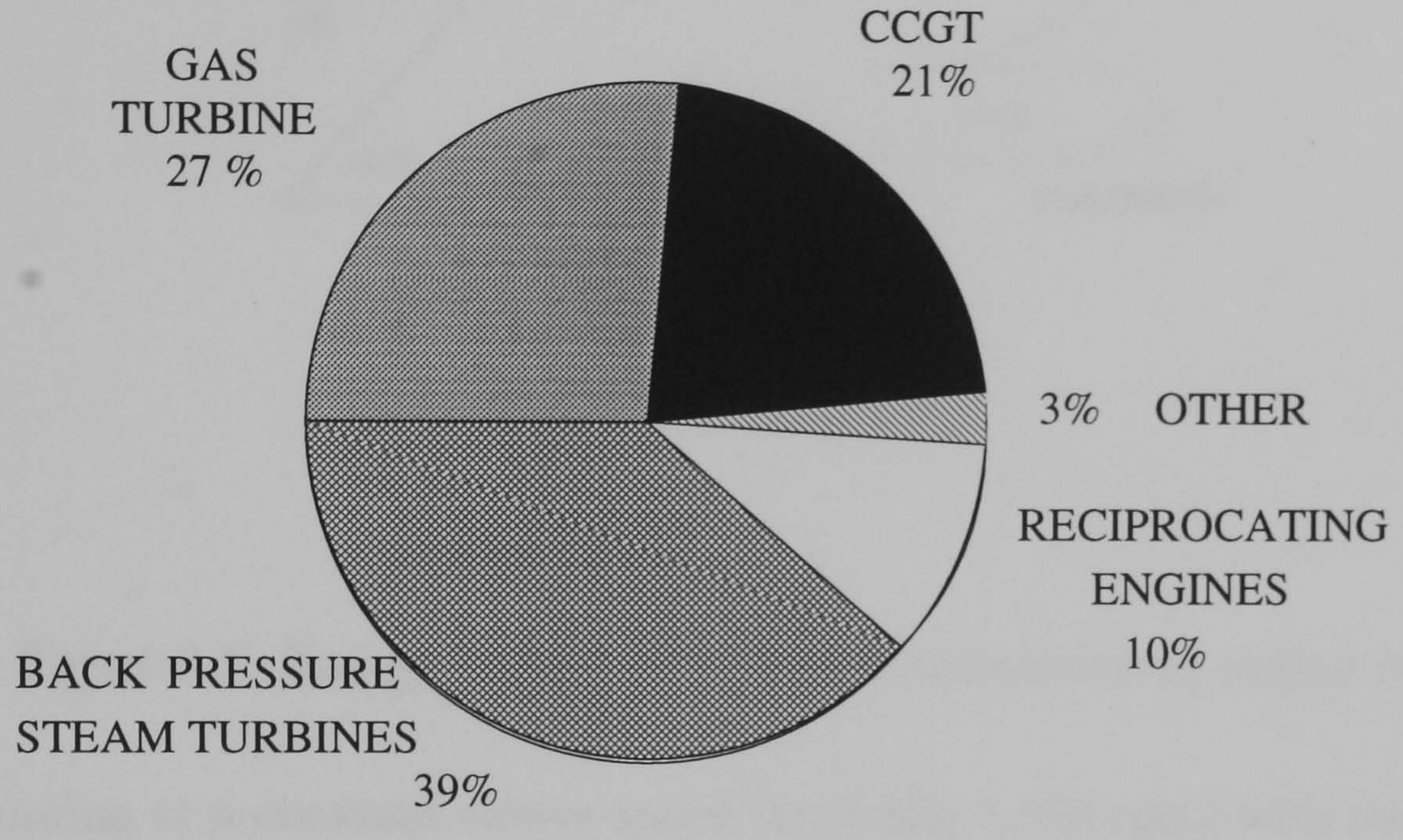


Figure 3.4: Market breakdown of the types of CHP plant used.

Reciprocating engines
The reciprocating engines used in CHP are internal combustion engines operating on the same familiar principles as their petrol and diesel engine automotive counterparts. Their shaft efficiency is inherently better than that of gas turbines. The usable heat-to-power ratio range is 0.5:1 to 2:1 and as the exhaust contains large amounts of excess air, supplementary firing is feasible and can raise the ratio to 5:1. Reciprocating engines and their lubricating oil must be cooled, therefore, there will always be a supply of heat in the form of hot water from these types of engines.

Reciprocating engines used for CHP generally fall into the following categories:

Spark ignition - these are often automobile derivatives with power outputs in the range 15 to 30 kW_e. Engine life is usually in the range 10,000 to 30,000 hours, compared with 2,000 to 6,000 hours for a car engine. The extended life is achieved

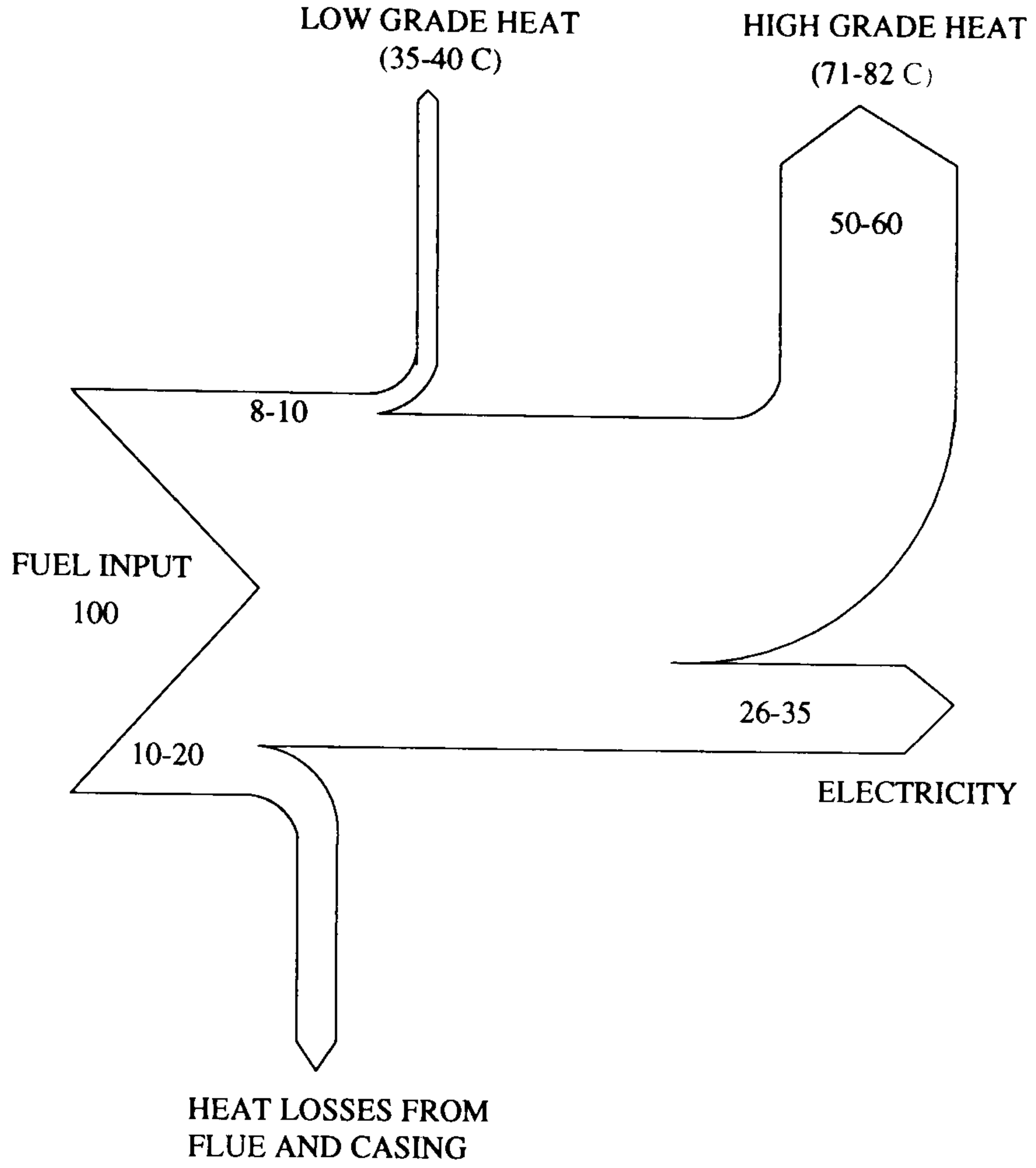


Figure 3.5: Energy balance of a typical reciprocating-engine CHP unit.

by running at a constant slower speed (typically 1,500 rpm) with steady load conditions. Converted petrol engines are small and light weight and have a relatively high power output.

Diesel derivatives - These spark ignition engines are generally used for electrical loads from 35 to 200 kW_e. The engines are normally substantially modified (pistons, heads, valve gear, ignition and fuel systems, etc.) to enable them to operate on natural gas. These modifications extend the engine's life considerably, generally to around 30,000 operational hours, and also increase the interval between servicing.

Spark-ignition gas engines are not normally used in large-scale industrial applications due to the limited number of engine sizes and the low grade of heat available from the engines.

Stationary engines - These are designed for electrical loads of up to $3MW_e$ and were originally used in industry or ships. They combine a long life with low maintenance costs. However, the capital costs of the systems are high.

Dual-fuel stationary engines - These are flexible engines, which are able to run on gas or gas oil. The additional fuel-supply systems required result in the need for more complex control and instrumentation systems, which in turn lead to increased capital costs.

Gas Turbines

These utilise pressurised combustion gases from fuel burned in one or more combustion chambers to turn a series of bladed fan wheels and rotate the shaft on which they are mounted. This drives the generator. Combustion gases are delivered to the power turbine at a temperature in the range of 900°C to 1200°C and exhausted from it at 450°C to 500°C; this exhaust is the source of heat energy to the site and makes the gas turbine particularly suitable for high-grade heat supply. The usable heat-to-power ratio ranges from 1.5:1 to 3:1.

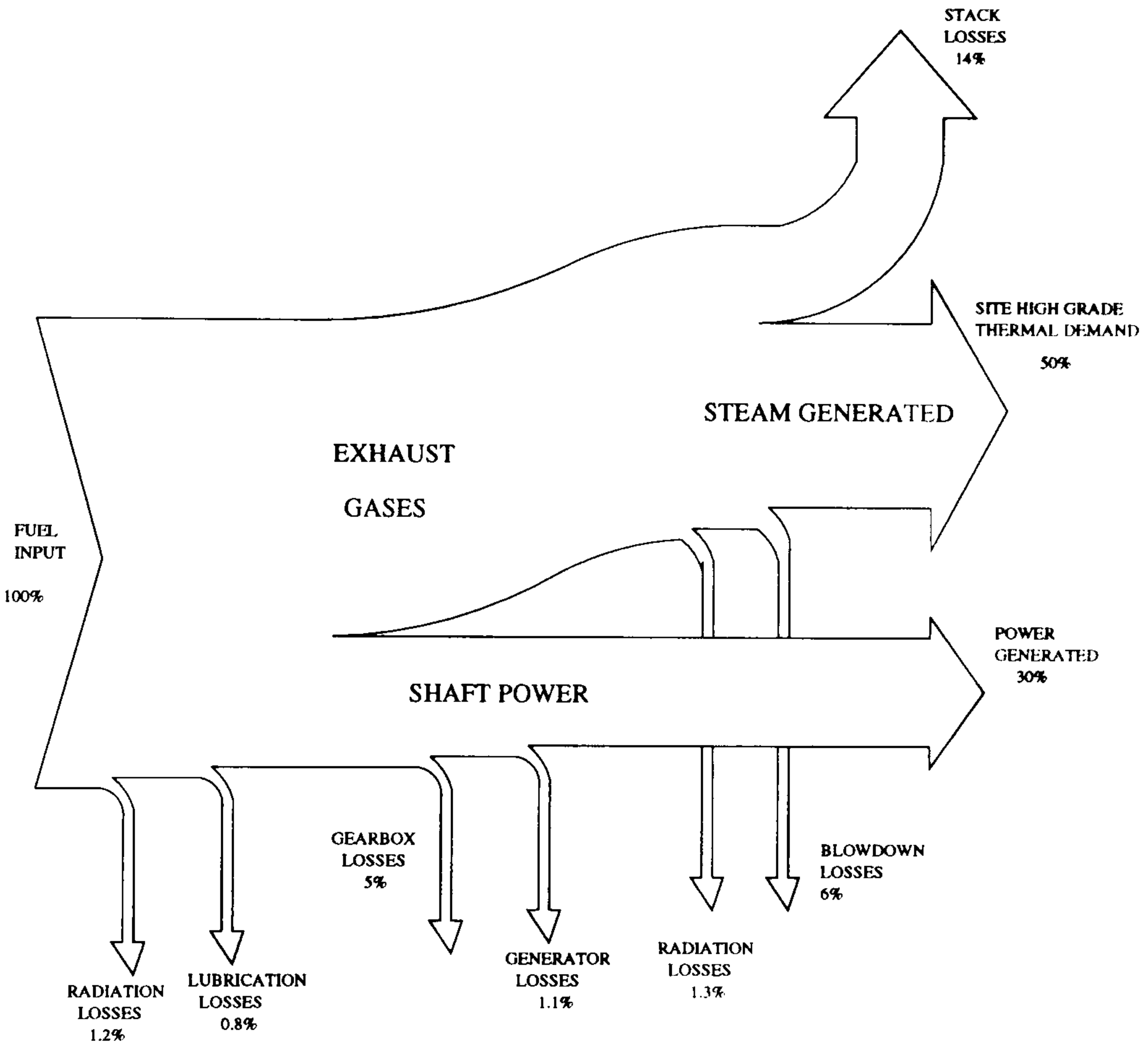


Figure 3.6: Energy balance of a typical gas turbine CHP Unit [6].

Steam Turbines

These are similar in principle to the gas turbines except that the pressure energy to drive them is provided by steam instead of hot gases. The power produced depends on how far the steam pressure can be reduced through the turbine. before being supplied to meet site's heat energy needs. Steam turbine sets are designated by their operating mode(s), eg. back pressure, pass out/back pressure or pass out condensed.

Back-pressure turbines - are the simplest design: all the steam that flows through the machine is exhausted from the turbine at the pressure required by the site.

Pass out/back pressure - Where more than one grade of heat is required. the higher grade is supplied by extracting steam ('pass-out' steam) at the appropriate pressure part-way along the turbine. The remainder continues to the exit therefore

Prime Mover Type / Characteristic	Spark ignition reciprocating engine	Compression ignition reciprocating engine	Open cycle gas turbines	Combined cycle gas turbines	Back pressure steam turbines	Pass out steam turbines
Fuel type used	Gas Biogas	Gas Biogas Gas oil Heavy fuel oil	Gas Biogas Gas oil	Gas Biogas Gas oil	Any fuel	Any fuel
Typical capacity range	30kWe to 2MWe	100kWe to 20 MWe	1 MWe and upwards	3 MWe and upwards	500 kWe and upwards	1MWe and upwards
Heat:Power ratio	1:1 to 2:1	0.5:1 to 1.5:1 (3:1 with boost firing)	1.5:1 to 2.5:1 (5:1 with supplementary firing)	1:1 (3:1 with supplementary firing)	3:1 to 10:1 and upwards	3:1 to 8:1 and upwards
Heat output quality	LPHW and steam (rare)	Steam and LPHW	High grade steam	Medium grade steam	Medium grade steam	Steam at 2 pressures
Electrical generating efficiency %	25 - 33	35 - 42	25 - 40	35 - 50	7 - 20	10 - 20
Overall efficiency %	70 - 78	65 - 70 (75 - 82 with boost firing)	65 - 80 (75 - 82 with supplementary firing)	73 - 80 (80 - 85 supplementary firing)	75 - 84	75 - 84
Capital cost £/kWe	550 - 850	500 - 800	500 - 1500	500 - 700	600 - 2000	600 - 2000
Operation & maintenance cost p/kWh	0.5 - 0.8	0.4 - 0.8	0.2 - 0.7	0.2 - 0.7	0.1	0.1

Table 3.2: Typical characteristics of various prime movers - efficiencies based on gross calorific values [22].

Item	Percentage of Fuel's Input Energy [a]					Temperature-°C	
	Engine Size Range[b] - kW					Flow	Return
	80-120	400-600	400-600 HT[c]	800-1,200	4,000-6,000		
Power Output	33	35	35	36	41	-	-
(variation within each size range)	(30-35)	(30-38)	- (31-41)	(35-42)	-	-	
Exhaust Gases	22	26	26	26	35	450	-
Engine Jacket Cooling System	33	25	22	24	9	95	85
Lubricating Oil-Cooling System	4	4	6	4	4	85	75
Charge Air-Cooling System	6	6	6	6	7	35	30
Outer Surface of Engine	2	4	5	4	4	-	-
	100	100	100	100	100		
Heat Recoverable at High	10	11	12	11	16	200	190
Temperature [d]	10	11	12	11	16	200	190
Heat Recoverable at Medium	15	16	39	16	22	120	110
Temperature [e]	15	16	39	16	22	120	110
Heat Recoverable at Low	54	47	47	46	38	80	70
Temperature [f]	54	47	47	46	38	80	70

Table 3.3: Typical Internal-Combustion Engine Performance data [23].

[a] The figures given in each size range are for a typical spark ignition turbo-charged IC engine operating at full-load on natural gas, with input energy taken at the lower heat value.

[b] Refers to shaft power output.

[c] Heat recovered to generate hot-water/steam at 200°C, Exhaust-gas temperature reduced to 230°C.

[d] Heat recovered to generate hot-water/steam at 120°C, Exhaust-gas temperature reduced to 150°C.

[e] Heat recovered to generate hot-water at 80°C, Exhaust-gas temperature reduced to 120°C.

[f] Engine modified to run at high jacket-cooling-water temperatures of typically 125°C flow and 115°C return.

generating further power, before exhausting to required industrial process at the lower pressure.

Pass out/condensing - The power output can be maximised by expanding the steam down to a vacuum using a condenser; this will produce very low grade heat for which there may be no on-site requirement to make the operation of the system viable.

Combined Cycle

Prime movers can be combined in a variety of ways to increase energy utilisation: they combine the open cycle of the gas turbine process with the closed cycle of the steam turbine. The effect of this unified process is that a higher proportion of the energy is converted to mechanical power rather than heat. In this way, a better match can be achieved between site demands and plant output. This is achieved by using a proportion of the heat rejected by the gas turbine to produce steam at a high enough pressure to drive a steam turbine; consequently, there will be two prime movers in series in this combined-cycle system. The maximum thermal efficiency of a simple CCGT is about 55% [69].

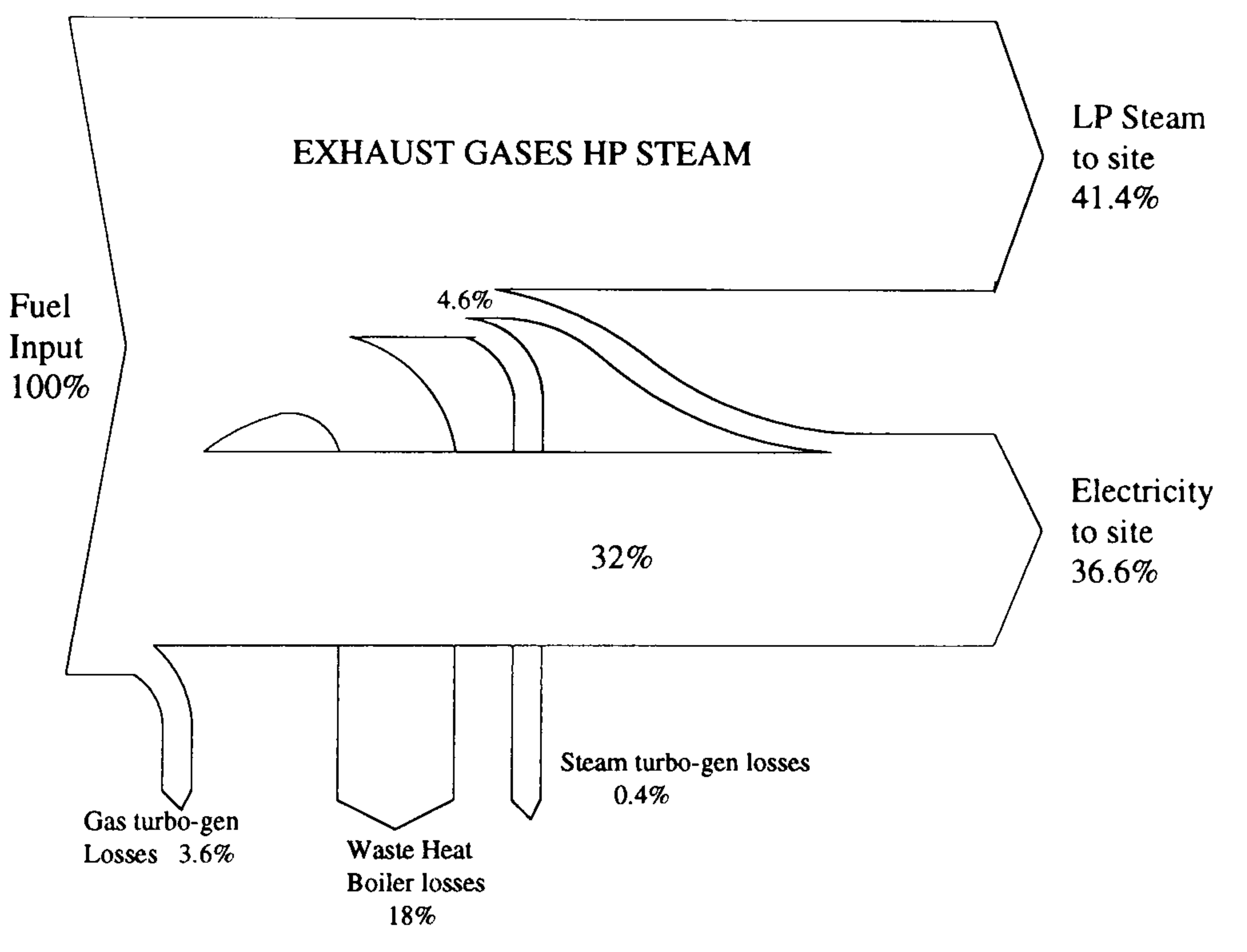


Figure 3.7: Energy balance of a CCGT CHP unit [6].

Reliability and Availability

The importance of these two factors for a fully successful CHP programme cannot be over stated as the CHP units will be required to operate throughout the year for at least 17 hours per day and 5 days per week and in many cases significantly longer even for continuous operation. In practice the prime mover will require regular breaks for maintenance and servicing, so resulting in scheduled shutdowns at least once a year.

The reliability of the prime mover is therefore a measure of its susceptibility to unscheduled breakdown.

Availability takes account of all non-operational time and can be defined as:

$$\frac{\textit{The number of hours in the year for which the chp unit actually operates}}{\textit{The number of hours in the year for which the chp unit is expected to be operational}}$$

Another factor, is the question of poor quality engines, which could cost up to 50% more to maintain over its life and might be uneconomic to repair before 10 years is up, when run continuously [70].

3.2.2 Fuels

The selection of a fuel for the operation of the CHP unit is usually the first decision made when appraising the options. In a few rare cases, there will be no choice as the sites location - eg. adjacent to a waste site - will dictate the most available, cheapest and appropriate fuel for use. Natural gas will usually be the first choice for new CHP installations for a variety of technical, environmental and economic reasons. However, its availability is not universal, so other fuels (e.g. fuel oil, coal or gas oil) might have to be considered in some cases. The internal combustion engine will run on a wide range of both liquid and gaseous fuels; although its equipment and process variations may be necessary (eg. landfill gas contains a high level of water vapour and therefore requires drying before the gas is burnt). A summary of the fuels used by CHP in 1995 is given in Figure 3.8. The use of coal by CHP was 3% down on the previous year while the use of natural gas was up 74% [10]; this trend has been occurring for several years and is expected to continue.

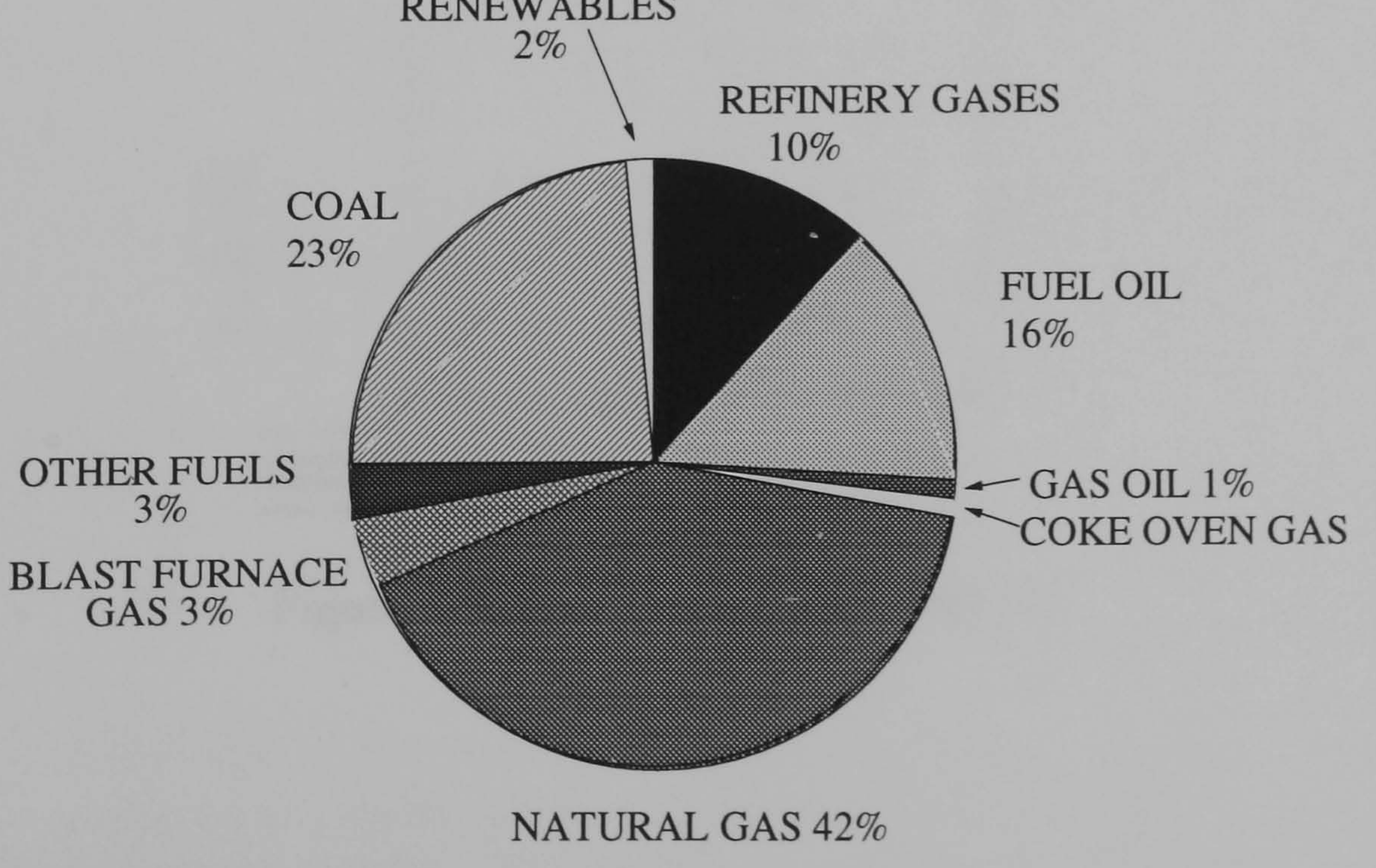


Figure 3.8: Types of fossil-fuel used by CHP plant, 1995 [3].

3.2.3 Generators

The generators can be categorised as either synchronous or asynchronous with both types producing 3-phase alternating current (ac) at 415V.
Synchronous generators operate in isolation from other generating plant (the grid). They use batteries for start up and can therefore, be used as stand-by generation. The frequency of the output current is determined by the speed of rotation.
Asynchronous generators are more efficient than synchronous generators for smaller units. They need the grid for magnetic excitation and will stop if the power from the grid is interrupted or disconnected. The frequency of the output current is automatically matched to that of the mains so that connection to the grid is simple. The power factor of the generator is always less than unity because it needs mains excitation. Capacitors can be used to minimise the penalty for a low power-factor; the CHP controls can be used to regulate the power-factor. Asynchronous generators cannot be used for stand-by generation.
Losses in electric generators are very small and typically range from 1% to 3% of the generators output. An electric generator requires little maintenance and has a life equivalent to an electric motor.

3.3 Small-Scale CHP

Most of the small-scale CHP units installed to date are based on spark-ignition gas engines and therefore have a heat-to-power ratio of between 1:1 and 2:1.

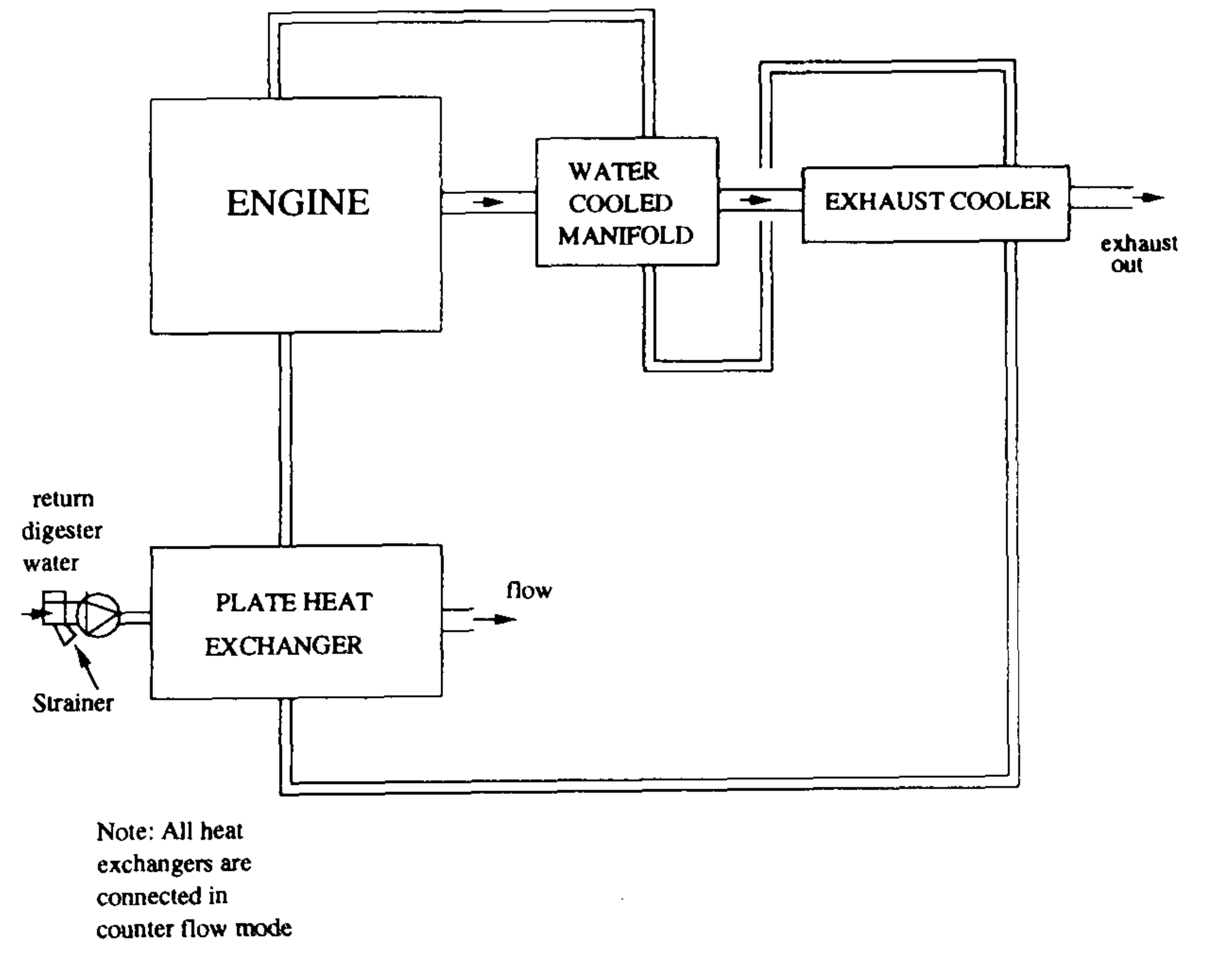


Figure 3.9: Heat recovery system [7].

3.3.1 Fundamental Components of a CHP Unit.

A small-scale CHP unit consists of five basic components (see Figure 3.10): An engine, an electric generator, a heat recovery system, a control system and an exhaust system.

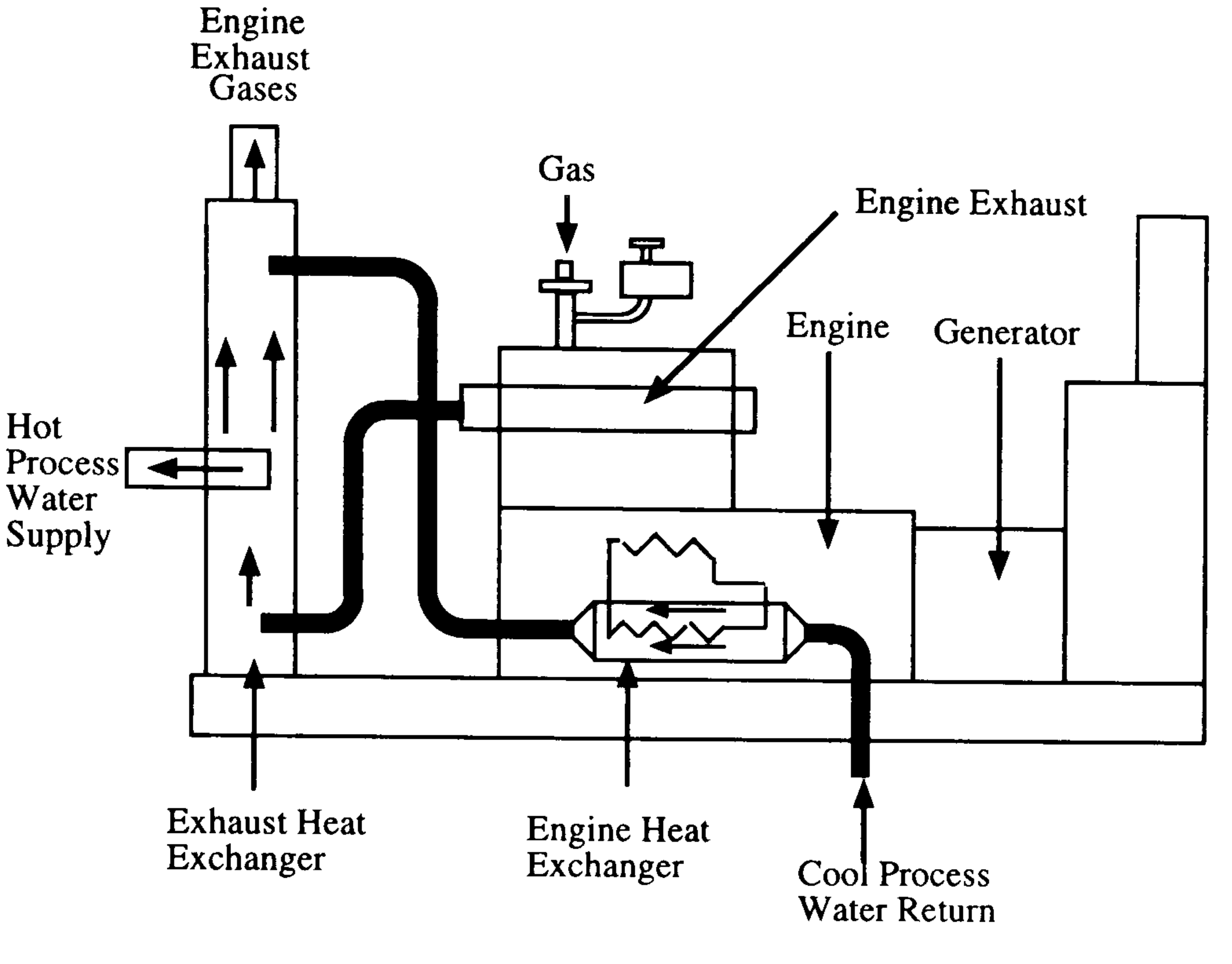


Figure 3.10: Small-scale CHP unit's component parts [8].

3.3.2 Heat-Recovery Systems.

After maximising the electrical-power output from CHP engines, the primary objective is to recover as much heat as possible for an acceptable fuel-burn. The heat-energy can be recovered from the generator, engine cooling circuits and exhaust gases. Over 90% of the available heat can be recovered. However this will require additional heat recovery equipment.

Source	Temperature °C	Recoverable Heat % Fuel Input
Engine Jacket	120	33
Exhaust	650	22
Exhaust Latent Heat	70	10

Table 3.4: Recoverable heat from CHP engines [8].

Typically, around 50% of the fuel input is recoverable as high-grade heat in the form of low temperature water (LTHW). A further 10% or more can be recovered as low-grade heat at 30 → 40°C. This compares with around 75 → 80% for a boiler operating at full-load [8]. The source temperatures and range of recoverable heat for a small-scale IC CHP unit are shown in Table 3.4.

Heat transfer: When the medium containing waste heat is a liquid or a vapour. which heats another liquid, then the shell and tube heat exchanger must be selected [71]. This is because both paths must be sealed in order to contain the pressures of their respective fluids. The shell contains the tube bundle. and usually internal baffles to divert the fluid in the shell over the tubes in the multiple process.

3.3.3 Modulation

Modulation, part-load operation or turn-down are the commonly used phrases used to describe the operation of CHP units at less than 100% electricity and heat output. Modulated operation is required - usually to protect the engine from overheating in water-cooled circuits - when a site's demand for heat or power falls below the maximum levels produced by the CHP unit. The aim of any future CHP system should be to get maximum output for as many hours as possible from the unit. Therefore, it is recommended that modulated operation be avoided completely or at least kept to a minimum where possible. Modulating the units will lead to a reduction in the operating efficiency - as manufacturers 'ratings' are based on continuous steady-state conditions - as well as a change in the proportion of heat-to-electricity produced. Additionally, maintenance costs are based on hours run for the CHP unit, so when operated at part-load the maintenance costs per kWh generated will rise. Collectively, these factors will in turn change the economics of the system, if the situation was not predicted at the appraisal stage of the CHP installation. Repeated cycling of operation should also be avoided. as this will shorten the life of the CHP units, since a large amount of wear takes place in the first few moments of operation, especially when the engine and lubricating oil is cold. Wear can be minimised be pre-pressurising or heating the system before start-up.

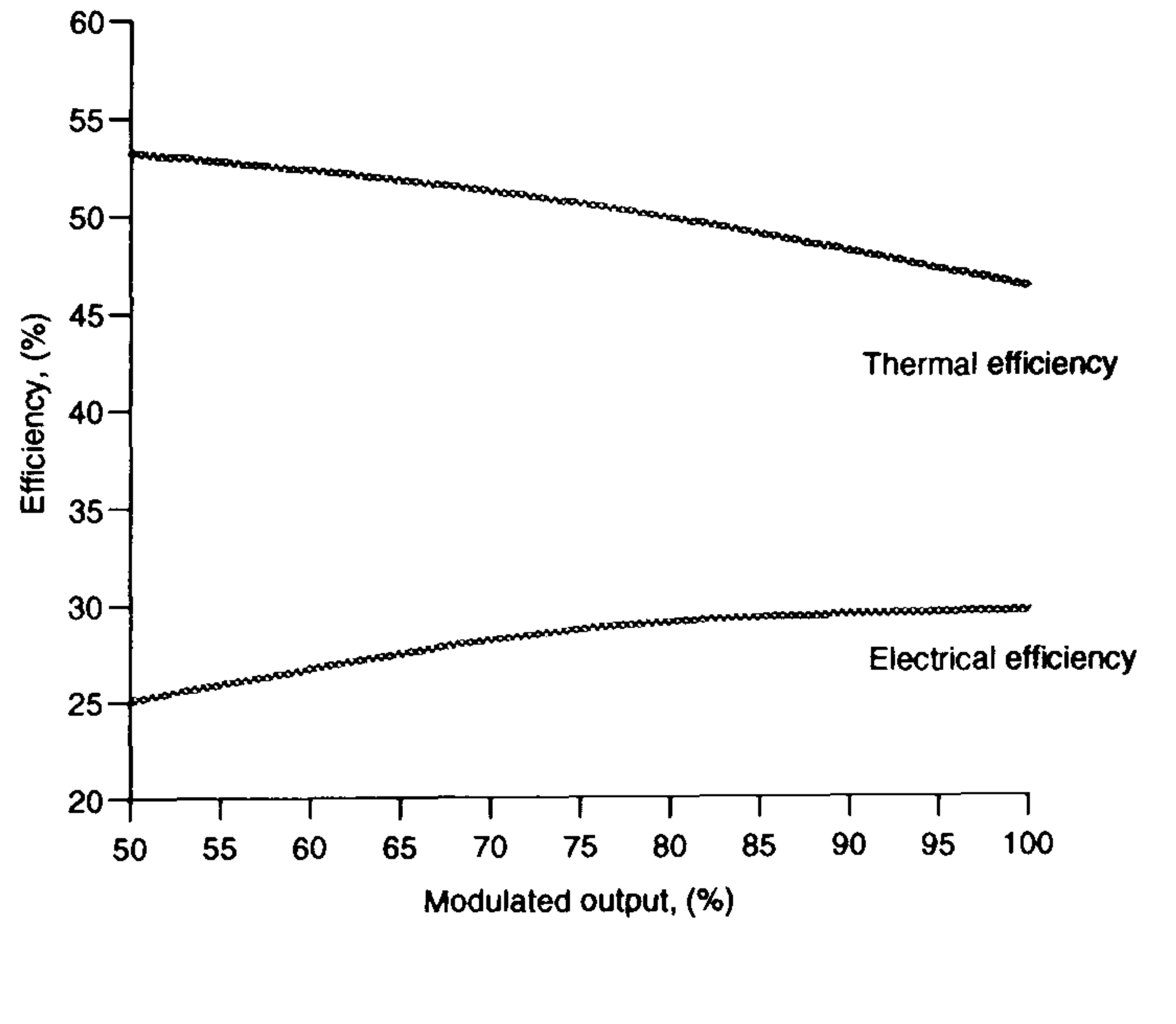


Figure 3.11: A typical 70 kW_e gas-fired reciprocating CHP unit's part-load performance.

3.4 Environmental Aspects of Energy Production

Carbon dioxide, together with many other gases are normal parts of the atmosphere, CO_2 being essential to plant life. However, if the proportion of CO_2 or any other gas in the environment deviates from the natural balance, then the long-term consequences could be dramatic for all planet life.
Concern about 'global warming' and 'ozone depletion' have increased steadily throughout the last decade. This rise in public concern has occurred mainly because of these subject's high profile in the media. As a result of this heightened awareness, scientific research has been undertaken around the world in order to find:

- conclusive evidence of the link between these environmental changes and the chemicals or processes with which they have been associated in order that any imbalance might start to be addressed.
- the significance of any environmental change for human and natural life on the planet.
- a structured approach for redressing the balance.

General research has shown that global average surface temperatures have increased by 0.3 to 0.6°C since the late 19th century, and 9 out 10 of the hottest years on record have occurred since 1983. Additionally, the link between the release and build up of CFCs in the atmosphere and ozone depletion has been proved [10].

The production of energy is one of the main contributors towards the accumulation of excessive amounts of polluting substances in the environment and especially CO_2 - see Figure 3.13. In this section, the pollutants associated with the generation of electricity will be considered.

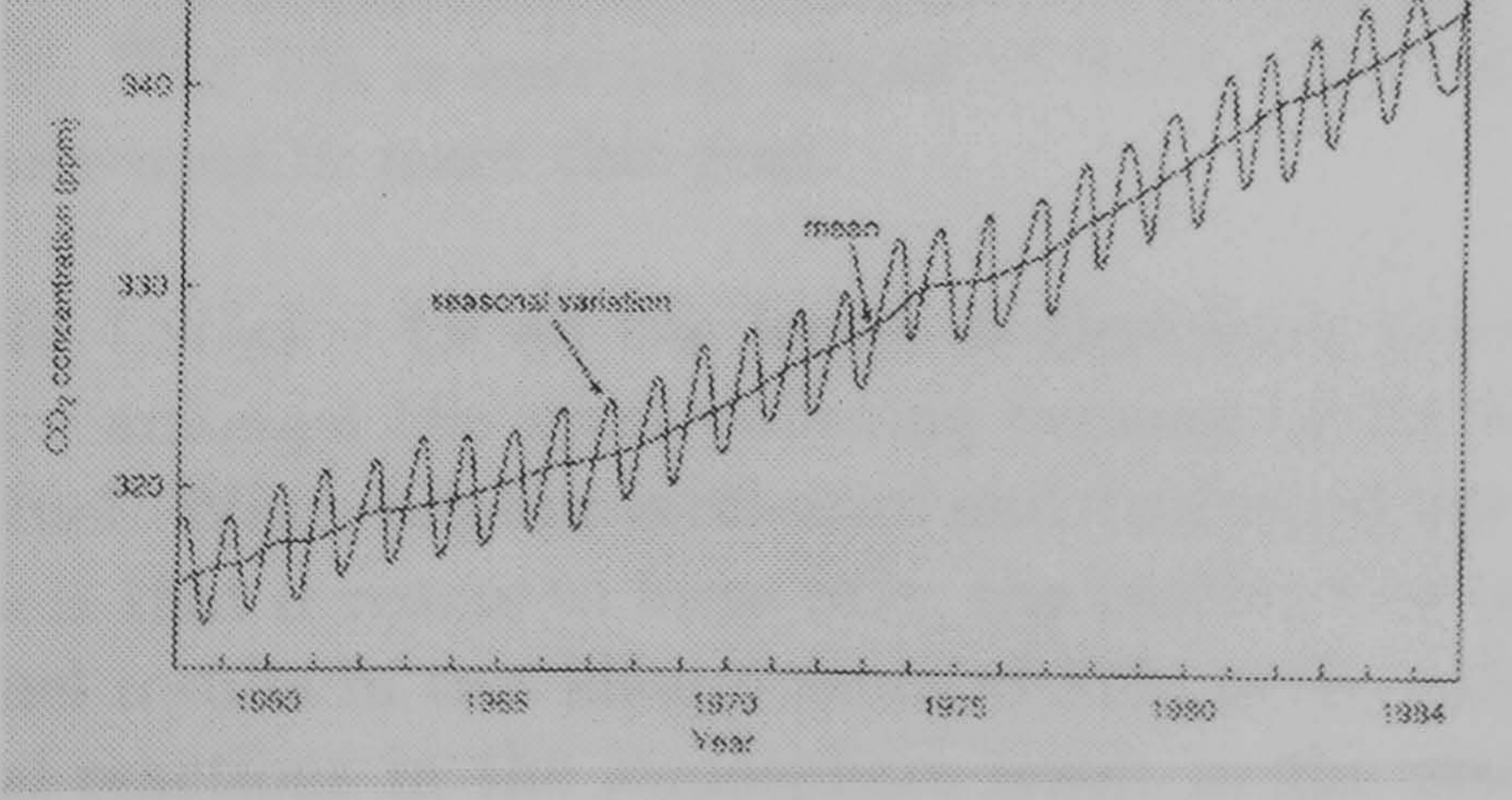


Figure 3.12: Historical carbon-dioxide emissions [9].

3.4.1 Fossil-Fuel Combustion

Fossil fuel combustion is a reaction between oxygen and the constituents of the fuel. The combustion process gives off heat which is usually a required and beneficial product of the process. All fossil fuels contain carbon which is the main combustible constituent; hydrogen being the other significant energy source.

Emissions from the combustion process
The burning of fossil fuels will give rise to the production of carbon dioxide (CO_2), sulphur dioxide (SO_2), nitric oxide (NO_x), methane(CH_4), carbon monoxide (CO), non-methane volatile organic compounds (NMVOC) and nitrous oxide (N_2O) [67]. The effect of these pollutants on the environment vary according to strength, location, quantity, weather conditions and the way in which they react with other chemicals already in the environment.

Carbon dioxide (CO_2) - The burning of all fossil fuels gives rise to the production of carbon dioxide, a major contributor to the cause of global warming. This is a gas which is produced in the greatest quantity by the combustion process. The aim of any combustion process is to convert all the available carbon to CO_2 in order to release the maximum available energy. In addition to emissions from the combustion of coal, for every molecule of sulphur dioxide absorbed by the calcium carbonate (lime) in the FGD system, one molecule of CO_2 is released. Ensuring that fossil fuels are used in the most energy-efficient way possible will reduce overall CO_2 output if all other factors remain constant. Therefore, CHP, with its superior energy efficiency, offers great scope for reducing emissions of CO_2 and other pollutants associated with the generation of electricity, through its efficient use of primary energy. The UK contributes about 2% to global man-made emissions of CO_2 which are currently estimated to range between 6,000 and 8,200 million tonnes per annum (of carbon) [10]. Because of increasing CO_2 build up in the atmosphere, the Government of the UK together with many others around the world agreed at the Rio summit in 1992 to reduce CO_2 emissions to 1990 levels by the year 2000 [72]. The UK is currently ahead of most of the other participating countries in its attempts to meet this goal.

Sulphur dioxide (SO_2) - Of all the forms of electricity generation, coal-fired power stations are amongst the most polluting because of the high sulphur content of the fossil-fuel. When sulphur is released and dissipated into the atmosphere, one of the results is that it reacts to form SO_2; the combustion of one kilogramme of sulphur in a fuel results in two kilogrammes of SO_2 in the exhaust [9]. Further complex chemical reactions in the atmosphere result in the production of acidic compounds such as sulphuric acid (H_2SO_4). These are a major cause of 'acid rain'. Acid rain damages soils, trees and buildings both in the UK and abroad. Additionally, medical evidence has emerged which links local pollution in an area with the poor health of the inhabitants. The cost of the damage to property and

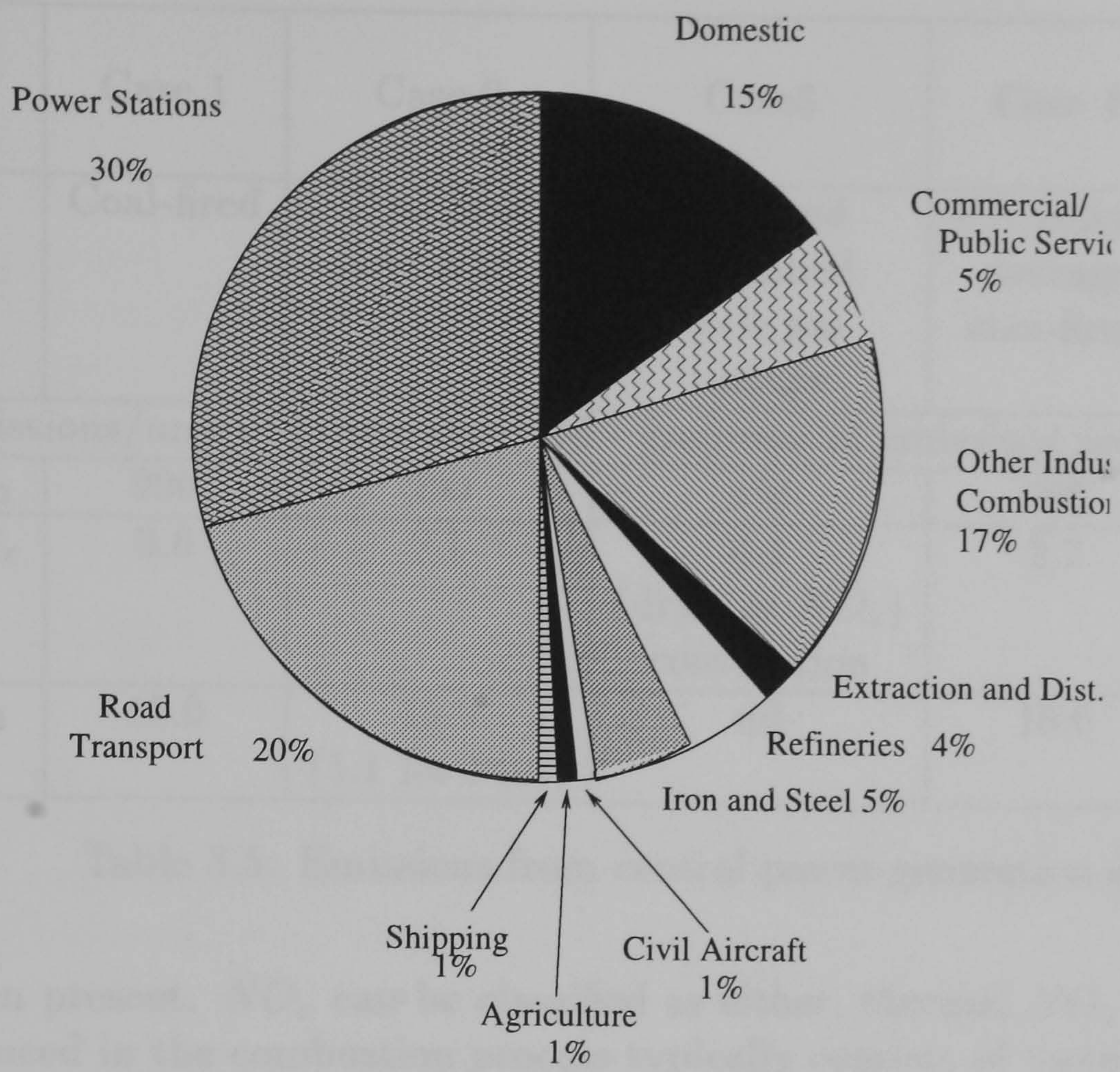


Figure 3.13: UK CO_2 emissions by sector [10].

health is difficult to predict accurately. Up to 90% of the SO_2 can be removed from the electricity-generating process by the installation of flue-gas desulphurisation (FGD) equipment which can be classified as either wet or dry. However, FGD plant will reduce efficiency by about 1% [73]. In some processes desulphurisation will lead to the production of of gypsum - a material used in the building industry - sulphuric acid (H_2SO_4) or sulphur. Selling such by-products can help offset the cost of recovering them. The most likely solution for the reduction of SO_2 production will come from the fuel-switch away from coal to gas as one of the primary fuels for electricity generation; this switch has occurred mainly as a result of economic factors.

Carbon monoxide (CO) - is produced by incomplete combustion of carbon; this is caused by a number of different factors in a combustion process. The rate of production is usually small, typically in parts per million of exhaust gases, but CO production is significantly increased when combustion is poorly controlled. CO is a toxic gas and in large quantities contributes towards local smog problems and respiratory problems.

Oxides of Nitrogen (NO_x) - NO_x is formed by the high temperature reactions of oxygen (O_2) with nitrogen (N_2) to produce nitric oxide (NO) and nitrogen dioxide (NO_2).The rate of formation of NO_x is affected by combustion temperature, residence time in the combustion zone and the concentrations of oxygen and ni-

	Case 1	Case 2	Case3	Case 4	Case 5
	Coal-fired	Coal-fired (low NO_x)	Gas-fired combined cycle gas turbine	UK supply average coal-fired	UK supply average all sources
Emissions/unit of power provided - grammes of emissions per kWh.					
CO_2	990	990	450	990	684
NO_x	3.6	2.1	0.4 (dry low NO_x) combustion	2.7	1.7
SO_2	15.0	15.0 (1.1 for FGD)	nil	15.0	9.0

Table 3.5: Emissions from central power generation stations [9]

trogen present. NO_x can be classified as either; thermal NO_x or fuel NO_x. NO_x produced in the combustion process typically consists of more than 90% NO and less than 10% NO_2. However, during atmospheric cooling, some of the NO reacts with ozone (O_3) and forms NO_2. This contributes to the ozone-layer depletion in the upper atmosphere and smog formation at ground level. NO_2 is also considered harmful to the respiratory system. Atmospheric reactions incorporating NO also lead to the formation of nitric acid (HNO_3) which contributes to acid rain [9]. Major UK power generators have an on-going programme of fitting low NO_x burners - which reduce NO_x by about 40% [74] - to large power stations.

3.4.2 CHP Can Help to Reduce Pollution

CHP produces energy from fossil fuel combustion. However, its higher conversion efficiencies lead to less emissions of most of the previously-mentioned gases per unit of energy - see Table 3.6. It has been estimated that every 1,000 MW of CHP installed is likely to save 1.25 million tonnes of carbon per year [75].
Other alternatives to traditional electricity generation which offer either a reduction in the levels of emissions produced or completely eliminate some of them include nuclear power, tidal power, solar power, hydro, wind, geothermal etc.. As usual, the solution to the problem is not as simple as it first appears. Therefore, the whole picture must be examined before corrective solutions are introduced. An example of this point is to consider the installation of hydro generated electricity, which, apparently at first site, produces electricity with no CO_2 emissions. However, if the cost of the construction of the giant dams, which are usually required for this process, in energy terms are considered then there will be CO_2 emissions associated with hydro-power. Of course, the same methodology could be applied

	CO_2 g/kWh	NO_x g/kWh	CO g/kWh	SO_2 g/kWh
Gas Engine CHP	580	15-25	1-2	Negligible
Heat from Gas-fired Boilers	360	0 - 1	0 - 1	Negligible
Electricity from Coal-fired Power Stations	990	2 - 3	Negligible	15
Net change in emissions to atmosphere by switching to CHP	-770	11 - 23	0 - 2	-15

Table 3.6: Emissions reductions by employing a gas-engine CHP[24],[9]

to the construction of CCGT or nuclear-power stations but the point is made that when considering the cost in terms of emissions of any specific system, all aspects of the entire situation must be analysed.

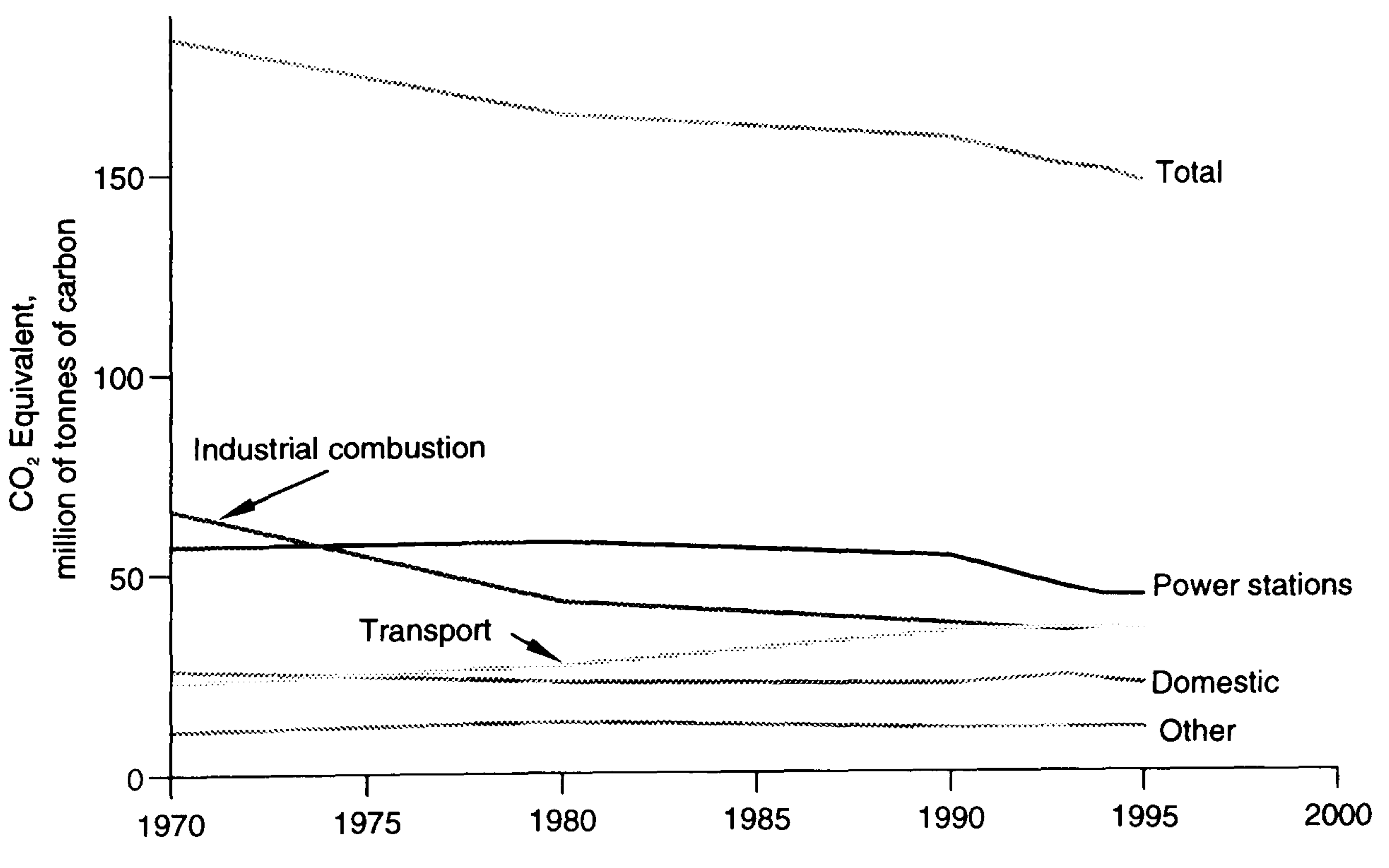


Figure 3.14: Atmospheric CO_2 emissions by source from 1970 to 1995 [3].

3.5 Economic Aspects of CHP

It can be seen that, from a purely energy-thrift point of view, CHP is often a wise option for energy production. However, when considering whether or not to install CHP plant, this is rarely the overriding factor. The attention of the of the potential investors will be on costs, savings and pay-back. The installation of CHP will require the expenditure of tens/hundreds of thousands of pounds by one of the interested parties. Therefore, the investment will need good annual operational savings and/or an acceptable pay-back period.

Generally an investment in CHP will only be sound if a number of important criteria are satisfied:

- There are simultaneous demands for adequate amounts of heat and electricity for at least 4,000 hours each year. Sites where the demand is likely to fall below this watershed are unlikely to give a satisfactory return on investment.
- CHP units are commonly sized for winter base heat-load in order to maximise savings against the high cost of electricity at this time of year.

3.5.1 Methods for Assessing Energy-Saving Investment Projects

Several main methods are consistently used for appraising CHP projects. These are Accounting Rate-of-Return, the pay-back period, and two discounted cash-flow methods methods based on interest rates; the Net Present Value and the Internal Rate of Return [4].

Accounting Rate-of-Return (ARR)
This method aims to indicate what level of return will be obtained by the investment in capital into the project. However, it takes no account of the timing of the savings. It is defined as:

$$ARR = \frac{average\ net\ annual\ savings\ (after\ depreciation)}{capital\ cost}$$

Pay-back
The pay-back period is defined as: the length of time required for the running total of net savings before depreciation to equal the capital cost of the project. The basic idea is that the shorter the pay-back time, the more attractive the investment. The method takes little account of timing of net savings but is widely considered as a useful first estimate.

Discounted Cash Flow (DCF)
DCF methods are based on interest rates and unlike the ARR and the pay-back methods, it will allow for the timing of the savings. It should be noted that a

project which produces higher savings in the early years facilitates making further investment in other schemes; the DCF methods try to 'weigh' the value of savings to reflect this point.

Net Present Value (NPV)
This method requires that the present value of all yearly capital costs and net savings throughout the life of the project are calculated. By summing all these present values (costs being represented as negative amounts and net savings as positive ones) a total will be obtained. This total is called the NPV of the project. If the NPV is negative then the project will be rejected. If the NPV is sufficiently positive then the project will be accepted. A discount rate will be required to carry out the calculation and this is usually set at a little above the interest rate for the cost of capital, thus allowing a margin for any risk due to uncertainties in assessing any future net savings.

Internal Rate-of-Return (IRR)
Allows the comparison of the new project with established projects by indicating a 'return' on the capital invested.

3.5.2 Energy Prices

The level of the electricity and gas prices are crucial to the economic viability of CHP systems. The best economic results are produced for CHP pay-back periods when electricity prices are high relative to gas prices. Additionally, it is important to have stability of energy prices over time so that long-term capital investments decisions can be taken without another risk factor.

Electricity prices
Electricity consumers can be divided into three different categories; (i) large - with a maximum demand (MD) of greater than 1 MW, (ii) medium - with a MD of greater than 100 kW and (iii) small - with an MD below 100 kW (see Figure 3.15). Since privatisation competition has been gradually introduced to each of these categories. Currently large and medium consumers are able to select their suppliers, and from 1998 all of the market will be open to competition. Competition has helped in the reduction of electricity prices in the last four years.

Gas prices
Privatisation of the gas industry in the UK has also increased competition, producing downward pressure on gas prices as show in Figure 3.16.

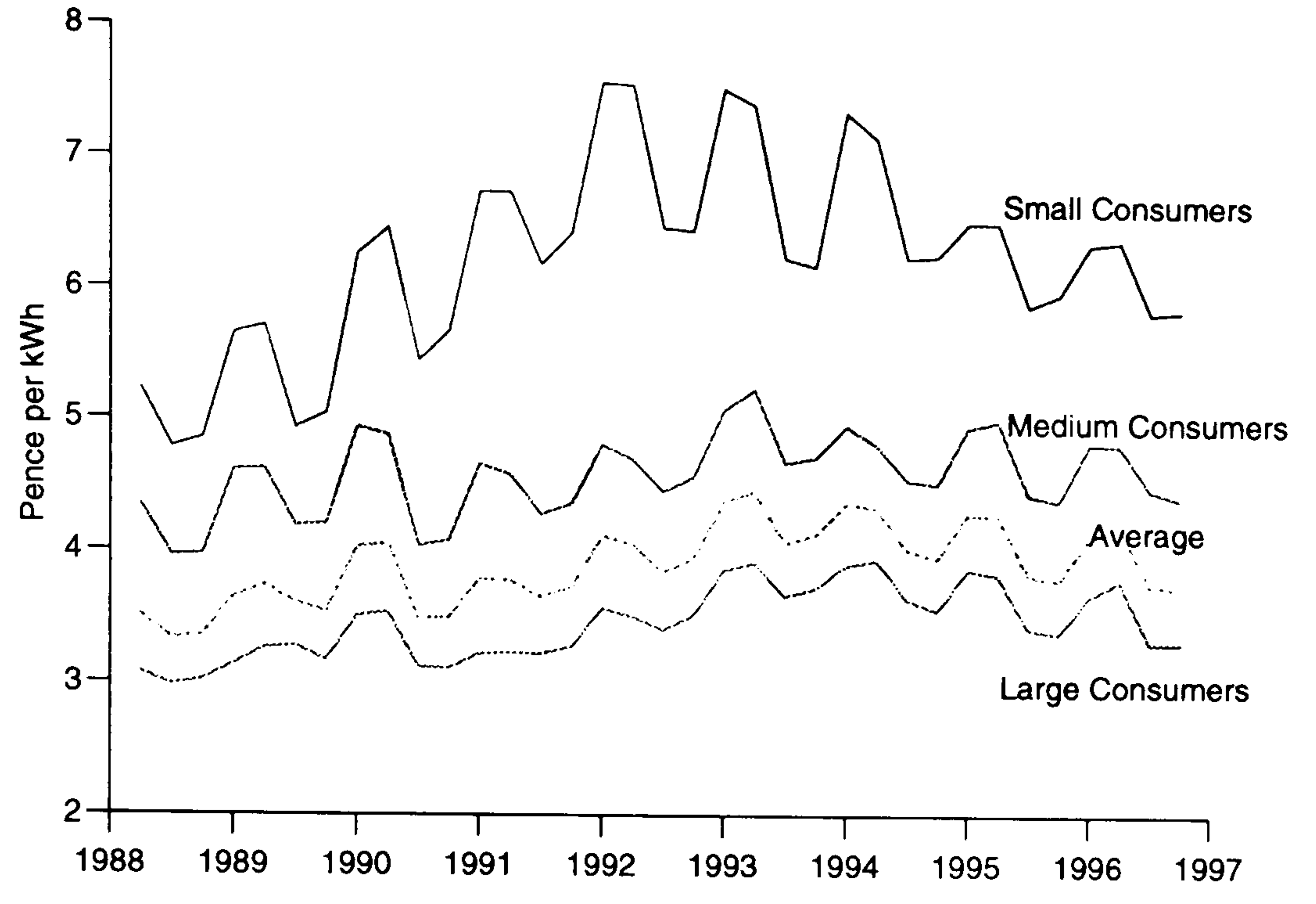


Figure 3.15: Historical UK unit electricity prices for different users [11].

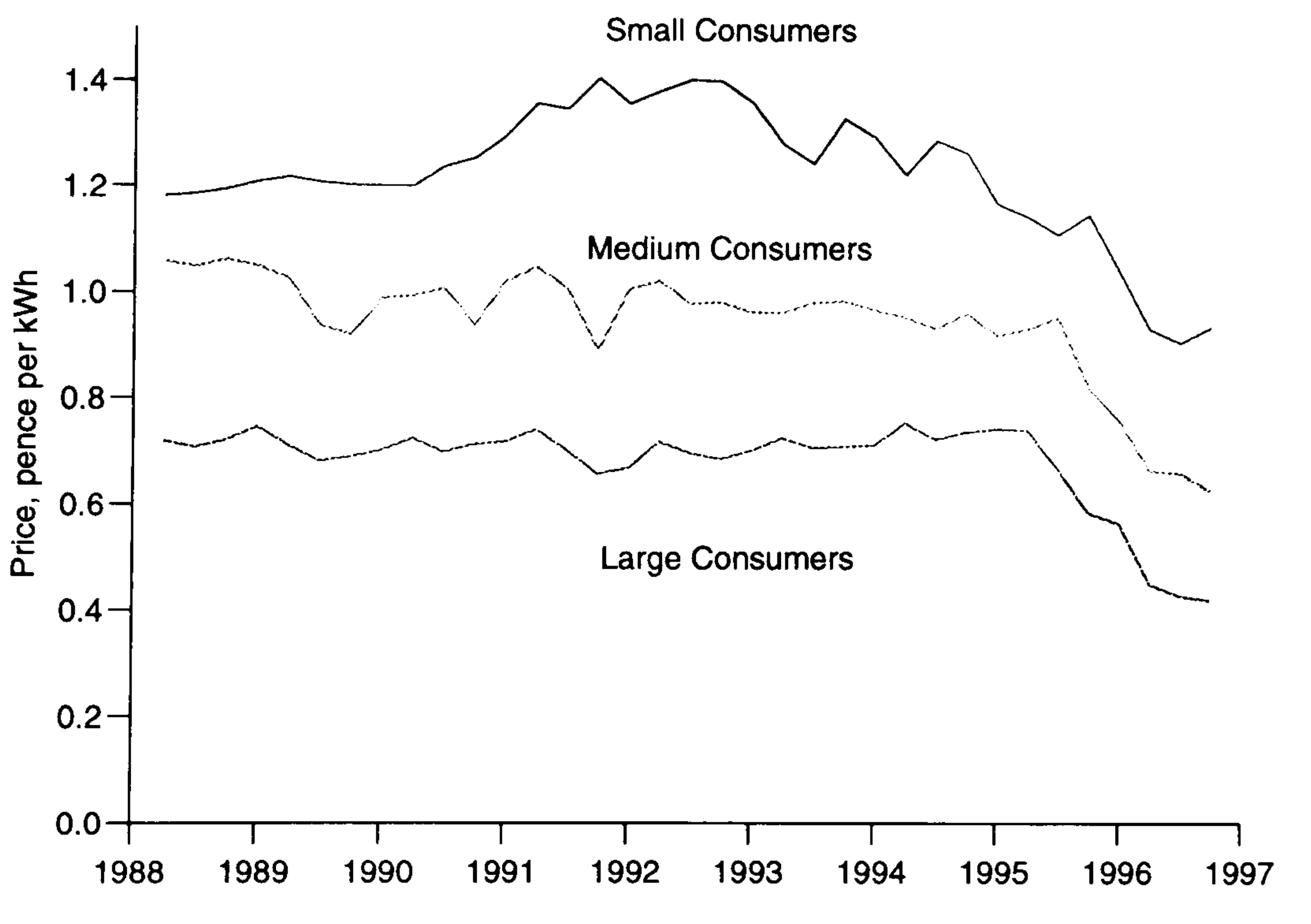


Figure 3.16: Historical UK unit gas prices for different users [11].

3.5.3 CHP Capital Costs

For the potential investor in CHP, there are usually two main purchase options:- (i) purchase the unit outright with a maintenance contract and then wait for the savings produced to give the planned pay-back; (ii) arrange an energy supply contract - usually termed Contract Energy Management (CEM) - with a CHP manufacturer, where the CHP unit is provided free of charge; the electricity is purchased at a discount from the owner of the CHP unit and the gas is bought separately from a supplier. This second option will provide a low risk alternative for the CHP investor. There are numerous variations of these two options, which may require a small contribution towards the capital cost thus giving a greater discount for the electricity supplied.

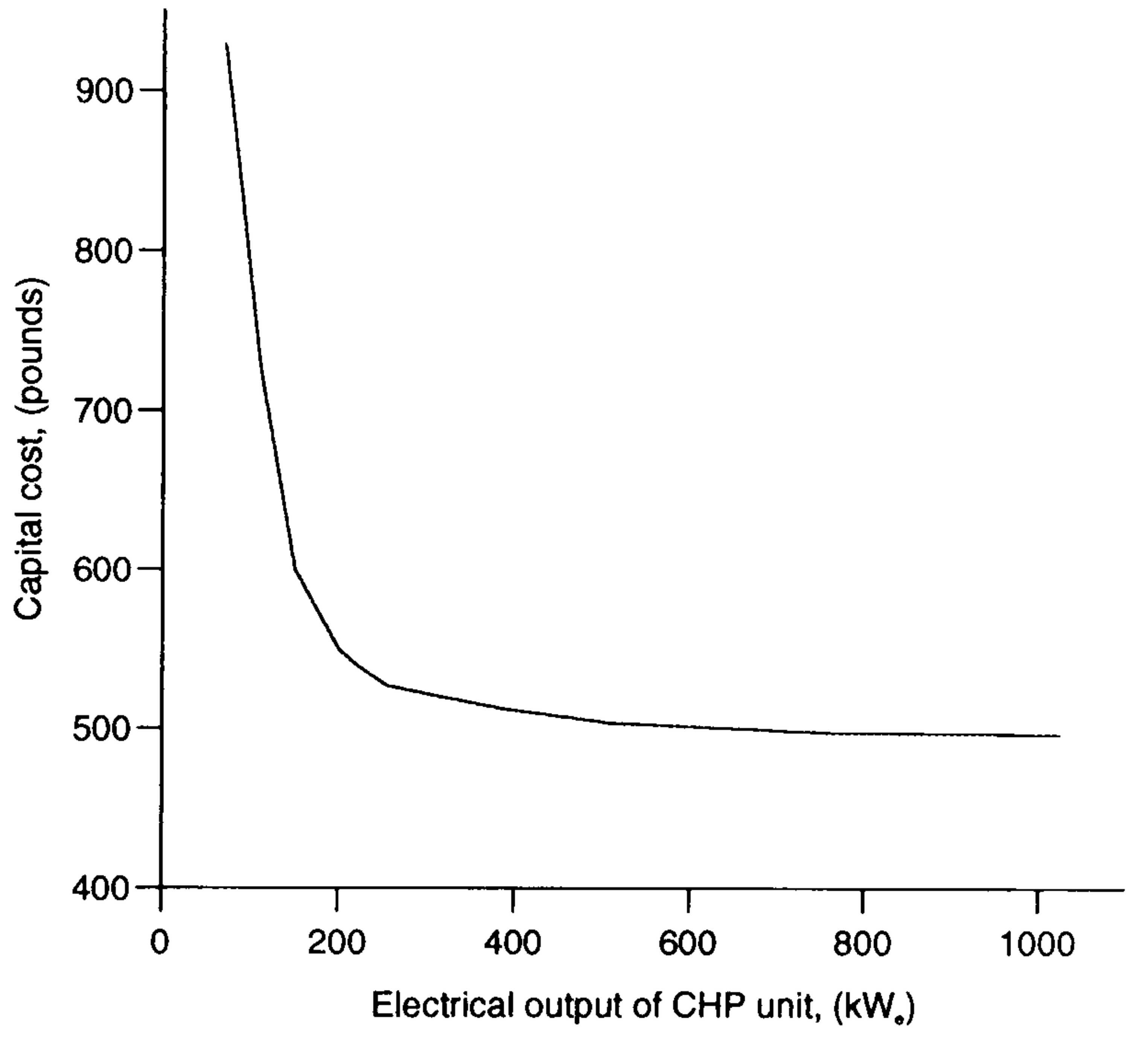


Figure 3.17: The capital cost curve for some typical small-scale CHP units..

3.5.4 CHP Maintenance Costs

Another important factor for the economics of CHP systems is the cost of regular servicing together with breakdown repair. Regular and thorough maintenance programmes will ensure that down-time, due to mechanical breakdown, is kept to the absolute minimum. Additionally, continuous maintenance will extent the working life of the CHP unit and allow the unit to operate as efficiently and effectively as possible. This will result in maximum economic savings being achieved. Maintenance costs can be high and will certainly be a significant proportion of the total running costs throughout the life of the CHP unit. Typical maintenance costs for small-scale CHP plant will range from 0.70 pence per kW for a 1 MW$_e$ unit to 1.13 pence per kW for a 32 kW$_e$ unit. Cost-savings should not be achieved through the reduction of the maintenance programme.

3.6 Political and Legislative Aspects of CHP

The UK Government's 2000 AD target for installed CHP capacity is currently 5,000 MW_e. This is an important driver in the market for the industry: it is expected that a government-set target will lead to the installation of a favourable framework to facilitate the achievement of the intended goal. This positive environment for the installation of CHP might include capital grants or tax incentives for investors in the technology, or a levy on energy prices for other forms of heat-and-power production. This could be implemented in the same way as the Non Fossil-Fuel Levy (NFFL), which currently subsidises generators of electricity which do not use fossil fuels for generation.

The electricity industry is regulated through the Office of Electricity Regulation (OFFER) - for an in-depth look at the electricity industry, see chapter 2. The CHP industry is affected by the regulations currently set in the market, which might be either positive or negative. For example, rules which govern the generation and export of electricity, or the unit price paid for it are crucial for the viability of some systems.

The origins of the current trend in energy efficiency can be traced back to the oil-price crisis of the 1970s, after which the Energy Technological-Support Unit was set up by the UK Government to promote energy efficiency in order to reduce the consumption of fossil-fuels.

Legislation

3.6.1 The Energy Act 1983

This Act provided the first legislative support for CHP by allowing the private generator to:
a) Buy electricity from the local electricity board for its own use or for the use of its customers.
b) Sell privately-generated electricity to the local electricity board.
c) Use the transmission and distribution system network of the local electricity board for its own use or the use of its customers.
This was evidence that the government was trying to encourage the development and application of CHP.

3.6.2 Electricity Act - 1989

The 1989 Electricity Act proposed the privatisation of the bulk of Electricity Supply Industry in England and Wales. A key feature of the legislation was the vertical disintegration of the industry into generation, transmission and supply functions.

Licensing

All those wishing to generate, transmit or supply electricity must apply to the Director General for a licence (OFFER leaflets - 'Business Licensing').

Licences fall into four categories:

1. Public Electricity-Supply Licence - currently only held by the twelve REC's. However, others may be granted it in the future. Holders are obliged to offer terms of supply to all premises in their region and to buy a certain proportion of their power from non-fossil fuel sources. It contains a use-of-system condition.

2. Second-tier Supply Licence - required by generators supplying direct to customers, public electricity suppliers wishing to supply outside their regions, brokers buying power from generators and selling on to consumers. The licence specifies which premises the holder is entitled to supply and includes a use-of-system condition.

3. Generating Licence - entitles the holder to generate power at any generating station.

4. Transmission Licence - permits the holder to transmit power over high-voltage lines and contains a use-of-system condition. At present, only the National Grid company and Scottish power companies have such a licence.

Most on-site plant is exempt from licensing where power is not exported.
The following is a list of exemptions for a supplier:

- 'de minimis' arrangements - where no more that 500kW is supplied at any one time;

- resale - where electricity is bought and immediately resold;

- off-shore - where supply is for off-shore consumers;

- own generation - where 51% or more of the plant's output is consumed on the same site as the plant and the remainder is sold to a licensed supplier;

- 'qualifying consumers' - including subsidiaries of the company operating the plant, those in which the operator has a 50% share holding and those separated by no more than one road, river, railway or building from the operator. Exports are not subject to a power limit;

For generators the following exemptions apply:

- 'de minimis' - where less than 10MW is generated on site;
- offshore - where generation is for offshore consumers;
- where the generated power is supplied to no more than one customer, the 10MW limit may be exceeded without requiring a licence;

Generators supplying RECs are required to hold a generating licence and have pool membership.

3.6.3 Government White Paper 1990

"This common inheritance" committed the EEO through the Best Practice programme to working towards the identified potential of a further 2,000 MW_e by the year AD 2000, thereby doubling the CHP capacity from 2,000 MW_e level in 1990 to 4,000 MW_e [76].

1993 Budget Announcement VAT was introduced on fuel which was widely expected to encourage energy efficiency and increase interest in CHP

July 1993 - The Government CHP target for AD 2000 is increased by 1000 MW_e of installed capacity to 5000 MW_e

April 1994 - Private generators can only supply to customers with a demand greater than 100kW. Smaller customers known as franchise customers are restricted to buying their power from local RECs until 31st March 1998, when the whole supply market will be opened to competition.

Recent years have seen more legislative help towards CHP, including:

- special powers for licensed generators to install heat mains (granted in the electricity act);
- new roles for Local Authorities were given regarding the purchasing and generating of electricity. For instance, the electricity Act (1989) allowed Local Authorities to sell power to any building they own without applying for a supply licence;
- a monitoring role for OFFER with respect to CHP;
- the housing Act (1989) provided a legislative basis for CHP joint ventures. The relevant regulations were declared in April 1995;
- exemption from the nuclear levy for on-site CHP generated electricity;

3.6.4 Relaxation of the Electricity Licensing-Regime

The licensing regime since privatisation has been revised to make it easier to export surplus power from on-site generation. In particular, the electricity order 1995 introduced the following changes, meaning that many more CHP operators became exempt from licensing requirements and hence payment of the fossil-fuel levy.

1) Increasing the level of supply at which a generation licence is required from 10 to 50 MW_e.
2) Allowing the temporary supply of above 50 MW_e of power in certain circumstances.
3) Extending the transitional exemptions granted to certain suppliers at electricity privatisation to 31st March 1998.
4) Relaxation of the 51% 'own use' rule.

Currently the Department of Trade and Industry (DTI) is consulting on the evolution of the licensing regime post 1998. On the 30th April 1996 the DTI announced plans for a further relaxation of the exemption condition in the run-up to full supply competition in 1998 to allow exempt suppliers to supply on-site, or over private wires, up to 100 MW_e to any commercial or industrial customers [77].

In Government, the policy lead for CHP is with the Energy-Efficiency Office (EEO) in the Department of the Environment (DoE).

3.7 The UK Market for Combined Heat-and-Power in 1996

An estimate of the technical potential for CHP (by ETSU) has suggested that CHP could ultimately supply as much as 25% (i.e. some 20,000 MW_e)of the UK's electricity generation capacity [68].

Combined Heat and Power (CHP) has been used in industrial applications in the UK and other industrialised countries since the last century and is one of the oldest forms of electricity generation. Over the last decade increased resources have been allocated in an attempt to achieve savings in energy consumption and reduce carbon-dioxide emissions through the wider use of CHP. The previous UK Government set a target of achieving 4000 MW_e of installed CHP capability by the year A.D. 2000 was revised and increased to 5,000 MW_e in 1993 [3]. 3,562 MW_e of capacity was in place by the end and accounting for more than 6% of the UK's generating capacity 1996[3] [78] (see Figure 3.18).

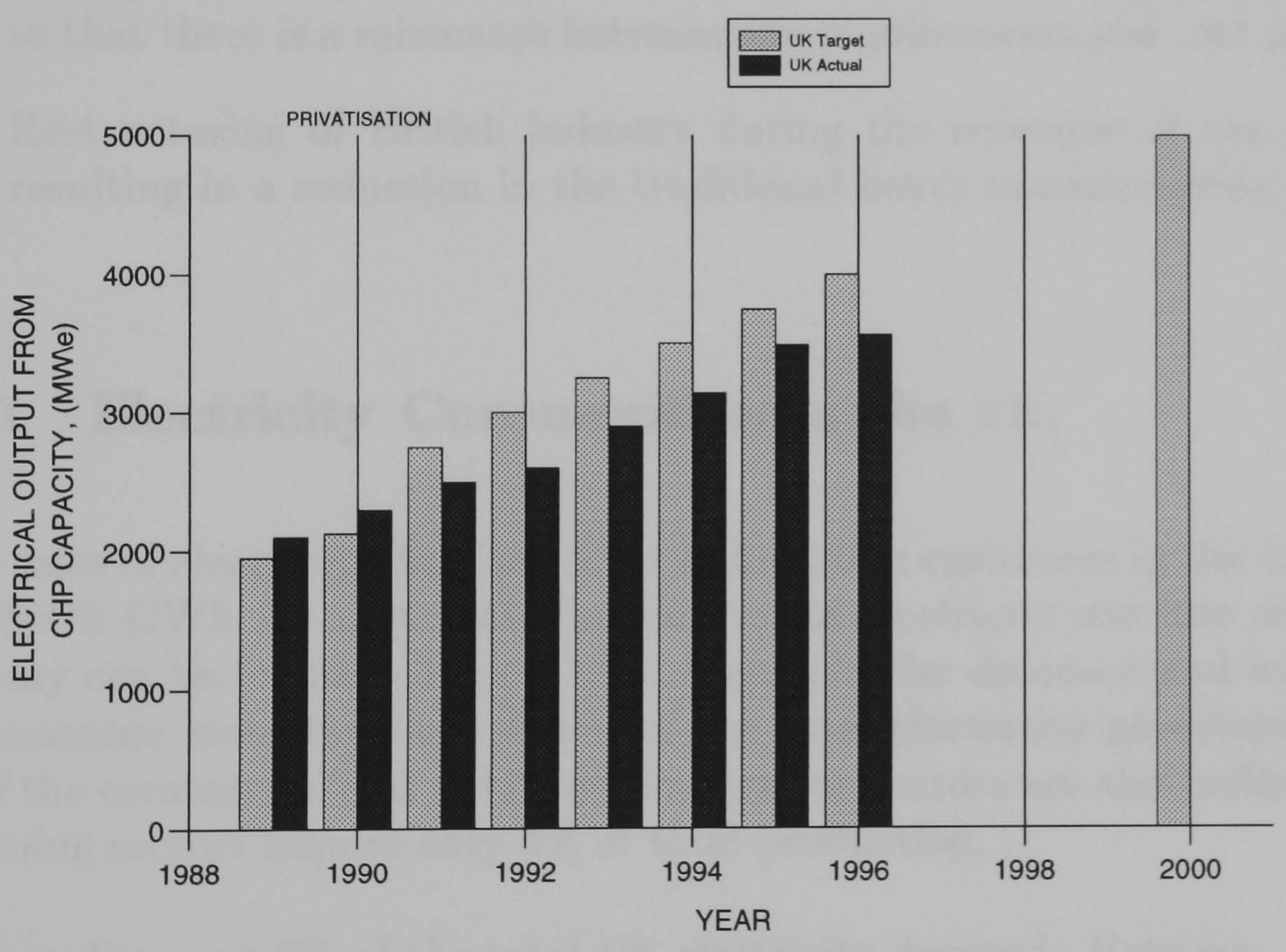


Figure 3.18: Government-set target for installed CHP capacity to the year AD 2000 [3].

The vast majority (about 96%) of installed UK CHP capacity is accounted for in large-scale tailor built plants installed in the booming industrial sector - with a further 200 MW_e is currently under construction - whilst approximately 4% of the capacity is located in small-scale CHP plants [79].

Since 1988 CHP capacity has almost doubled, representing an average growth rate over the period of 9% per annum. Growth in 1996 fell below this average at 2%. Past, present and future growth is partly dependent on the rate of retirement of old plants as well as the rate at which new plant are built. In a recent policy document, the Labour Party has proposed raising the government's target for CHP to 10,000 MW_e by AD 2010 [62]. This would require a doubling of capacity over a ten year period even if the target for the year 2000 can be achieved. The market could expand further if, and when, sufficiently inducing Government incentives (e.g. via the Energy-Saving Trust) are introduced to encourage the installation of CHP units. The latest Department of the Environment (DoE) estimate suggests an 'economic potential' for CHP of 12,000 MW_e.

Before the present revival in CHP capacity there was a period of decline in capacity between 1977 and 1988 which came about as a result of three factors:

1. Reductions in process industry's site heat-to-power ratios resulting in steam turbine plant being oversized for heat output and thus, part-loaded and inefficient.
2. Changes in the process operations requiring lower or higher pressure steam so that there is a mismatch between site requirements and CHP plant output.
3. Restructuring of British industry during the recession of the early 1980's resulting in a reduction in the traditional heavy manufacturing base.

3.7.1 Electricity Consumption in the UK.

Total sales of electricity distributed to 26,6 million customers in the UK amounted to 298,878 GWh for 1996. The breakdown of electricity use into sectors of the economy can be found in Figure 3.19. Together, the domestic and industrial sectors consume more than two-thirds of the total electricity generated in the UK, and if the commercial and public administration sectors are also included then the remaining sectors require only 6% of total production.

CHP supplies over 6% of the total UK electricity demand. However, a significant proportion of this market is not currently available to CHP. For example, the domestic sector which accounts for 36% of electricity sales makes little use of CHP, although some units have been installed in residential blocks of flats. The majority of the demand in the domestic sector comes from the individual housing units which would have a base demand for heat and power significantly below the smallest CHP units which are commercially available today. However, this sector does offer potential for the future with domestic CHP units which can offer 2-5kW_e output currently under development. This technology still requires changes in demand-load patterns for the house to enable peak demands to be satisfied as the micro-scale CHP units will have a relatively small electricity output.

	Percentage of total	
Fuel type	1992	1996
Coal	60.0	42.0
Nuclear	23.5	28.5
Gas	2.0	21.0
Oil	10.5	4.5
Imports	2.0	2.0
Other fuels	1.5	1.5
Hydro	0.5	0.5

Table 3.7: Fuel used in electricity generation for 1992 and 1996[3]

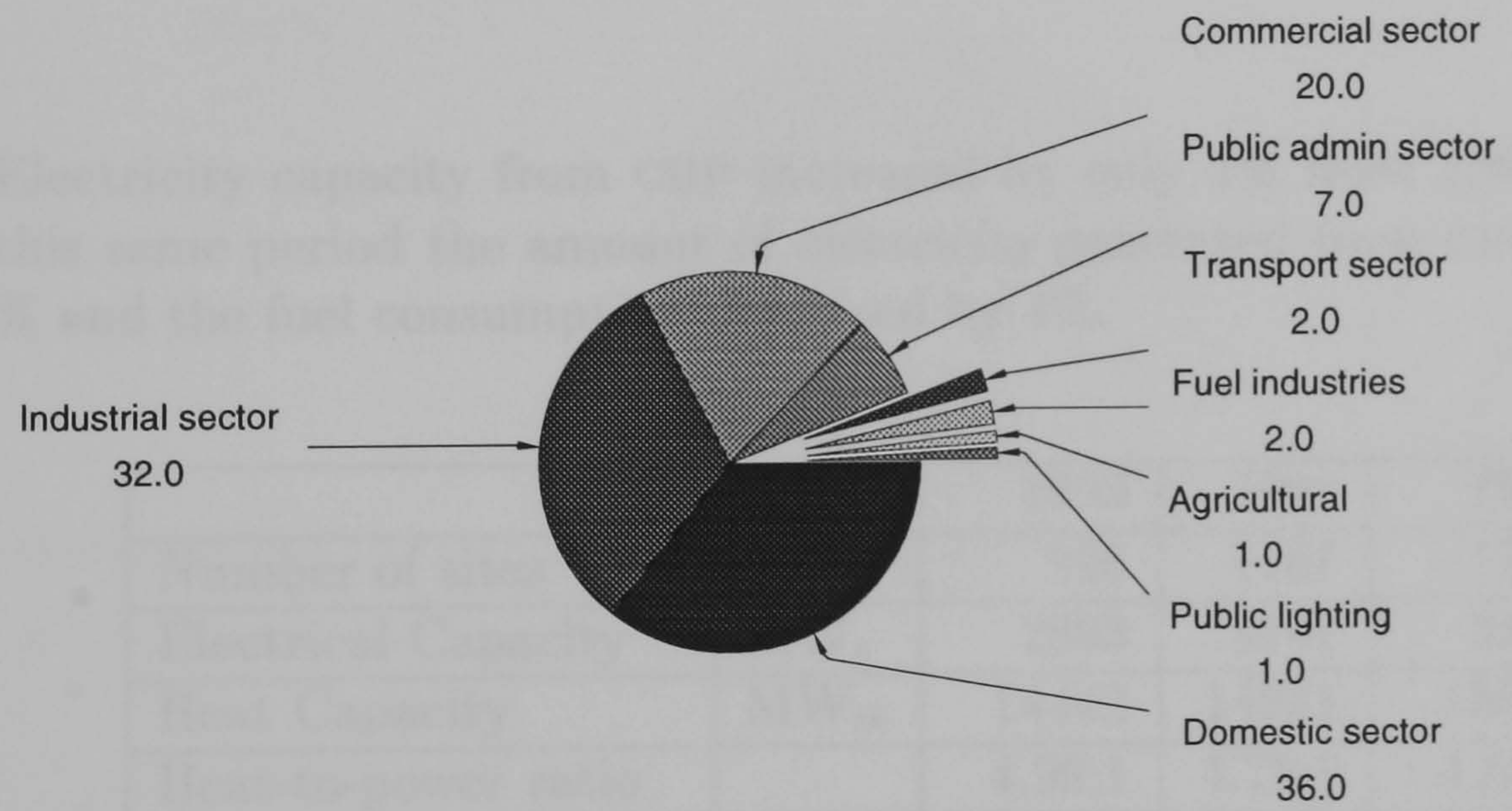


Figure 3.19: Electricity use by sector in the UK: 1996 [3].

3.7.2 The Current UK Market for CHP

In 1996 19,081 GWh (6.4% of the UK market) of electricity and 63,978 GWh of heat were produced by on-site CHP units [3]. In total there were 1,336 sites with an installed CHP capacity of 3,562 MW_e and 14,983 MW_T - see Table 3.8. 303 of these were considered to be in the industrial sector, with the other 864 in the commercial, public and residential sectors. Figure 3.20 and Table 3.8 indicate that the majority of CHP capacity is supplied by a small number of large units (above $10MW_e$) which gives large-scale CHP more than 96% of the UK market. Conversely small-scale sites account for over 80% of installations (see Figure 3.21 and Table 3.8).

Electrical Capacity	Number of Installations	Share of total (%)	Total elec Capacity	Share of total (%)
Less than $100kW_e$	674	50.4	37.1	1.0
$100kW_e$ - $999kW_e$	454	34.0	111.8	3.1
$1MW_e$ - $9.9MW_e$	144	10.8	587.5	16.5
Greater than $10MW_e$	64	4.8	2,825.9	79.3
Total	1,336	100%	3,562.0	100%

Table 3.8: CHP installations and capacities: 1996 [3].

Electricity capacity from CHP increased by only 2% from 1995 to 1996. During this same period the amount of electricity generated from CHP plant rose by 7.5 % and the fuel consumption increased by 4%.

	Unit	1993	1994	1995	1996
Number of sites		996	1167	1277	1336
Electrical Capacity	MW_e	2893	3141	3487	3562
Heat Capacity	MW_{th}	14442	14931	15833	14983
Heat-to-power ratio		4.99:1	4.75:1	4.54:1	4.21:1
Fuel input	GWh	101,650	92,566	109,831	111,299
Electricity generation	GWh	14,171	12,152	17,761	19,081
Heat generation	GWh	58,418	57,368	64,345	63,978
Overall efficiency	%	71.4	75.1	74.8	74.6
Load factor	%	55.9	53.1[1]	58.1	61.1

Table 3.9: Summary of CHP statistics since 1993 [3].

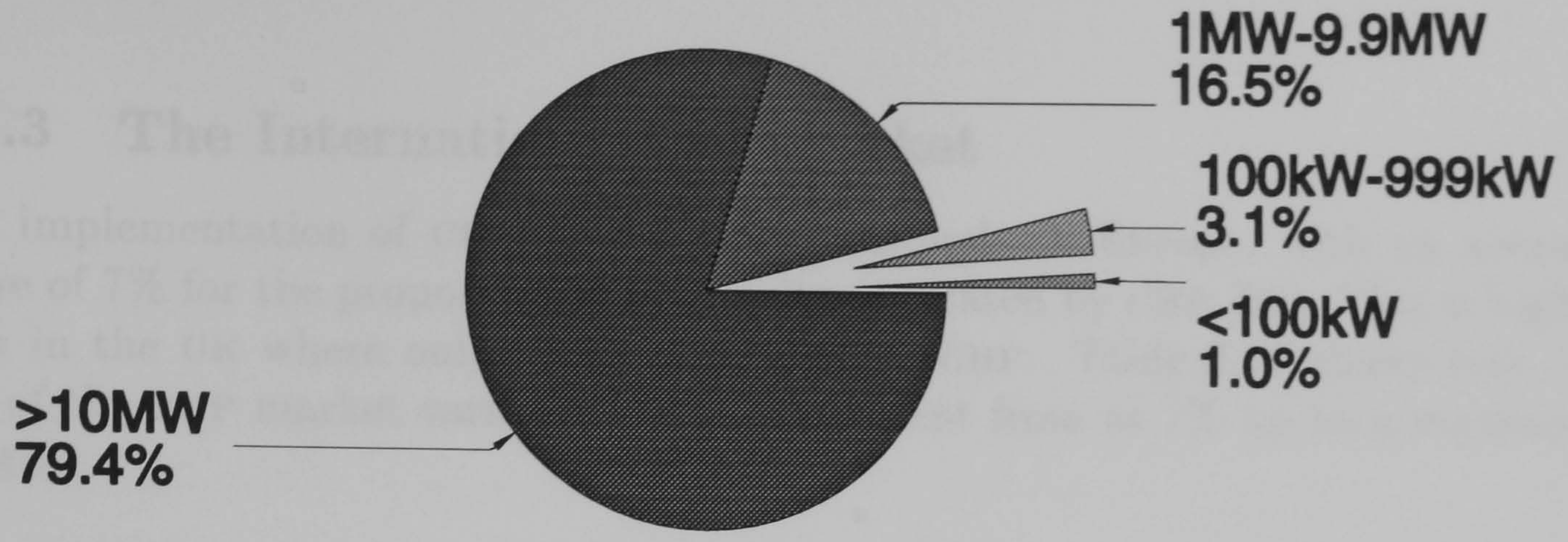


Figure 3.20: CHP market segmentation by capacity: 1996 [3].

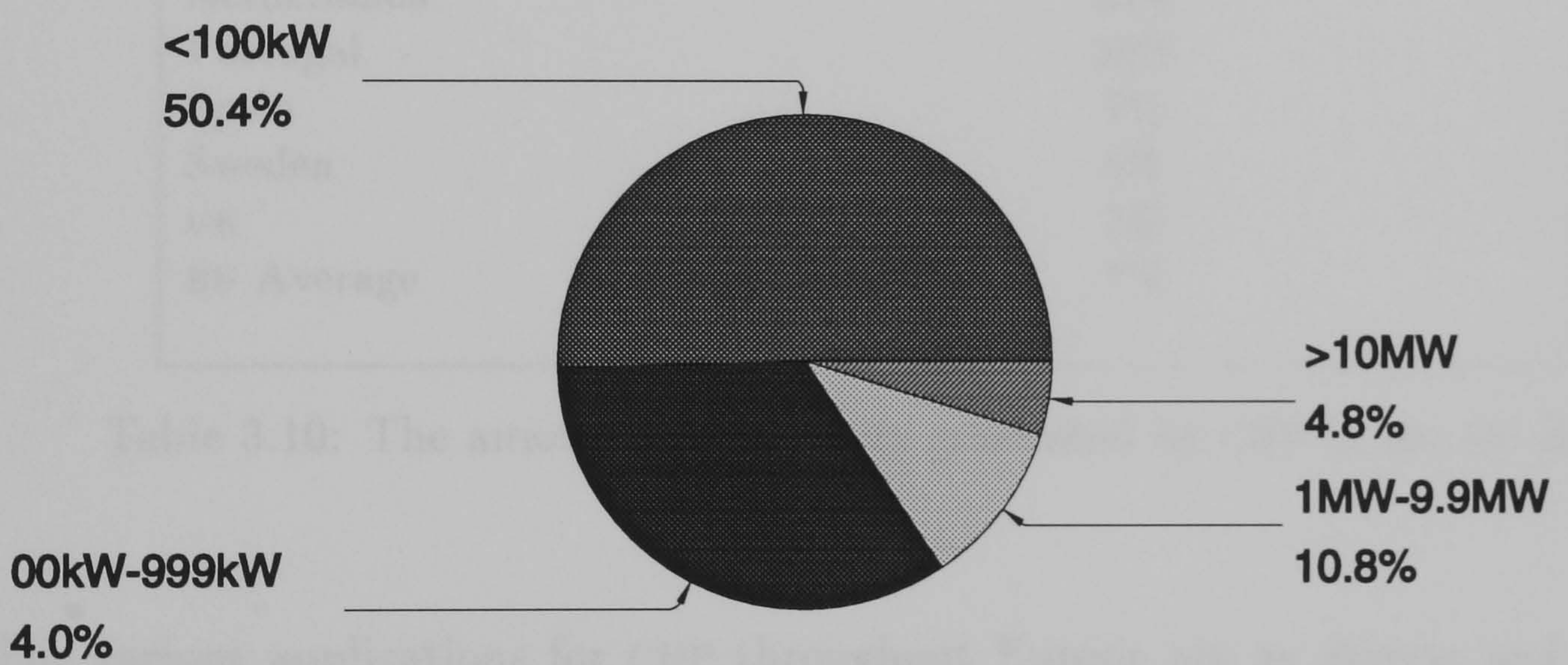


Figure 3.21: CHP market segmentation by number of sites: 1996 [3].

3.7.3 The International CHP market

The implementation of CHP is widespread throughout Europe, with an average figure of 7% for the proportion of electricity generated by CHP [25]. This is higher than in the UK where only 5% is generated by CHP. Table 3.10 shows how the size of the CHP market varies across the continent from as 1% up to a maximum of 34% .

COUNTRY	PROPORTION OF ELECTRICITY DEMAND MET BY CHP
Austria	13%
Belgium	3%
Denmark	29%
Finland	29%
France	1%
Germany	10%
Greece	3%
Ireland	2%
Italy	10%
Netherlands	34%
Portugal	10%
Spain	7%
Sweden	6%
UK	5%
EU Average	7%

Table 3.10: The amount of electricity generated by CHP in the EU [25].

The various applications for CHP throughout Europe are as diverse and varying as the utilisation rates in the specified countries. From Table 3.10 it can be determined that there is a rough divide between the northern European countries - where CHP capacity forms a greater proportion of the electricity production - and the southern European countries where CHP plays a less significant role. There are exceptions to this rule, with France producing only 1% of its electricity through CHP. This is partly because of the abundant supply of relatively cheap nuclear produced electricity, with which CHP finds it hard to compete on a cost basis. Italy, on the other hand, lies in the south of Europe and produces significantly more electricity from CHP than the European Union (EU). average. These factors, together with the cross-frontier import and export of electricity and government backing, begin to illustrate the various range of influencing factors which will carry a great weight in determining how CHP develops in Europe in the coming decade.

3.8 Summary

This chapter has presented an overview of the technical, economic and environmental aspects of CHP in the UK. CHP is clearly a technology that can provide useful energy in a more efficient and consequently less polluting way and would be the obvious choice for energy production if the decision were to be made on these grounds alone. Unfortunately, this is not the case as CHP must satisfy certain economic criteria as well. Whilst it is possible to fix the energy savings and emission reductions achieved from CHP for a particular installation at an identified site, it is not possible to predict with any degree of certainty future electricity or gas prices. This means that the economic viability is continually shifting for CHP systems, therefore, that installation which would be economic viable at 'today's' energy-rates might not be so in future and vice versa. This dilemma suggests that it would be appropriate (for the longer term view) to move the emphasis of the savings produced by CHP away from a purely financial basis towards the energy and environmental savings which could be achieved. From this point, it can be shown how the energy efficiency and environmental benefits can be quickly converted to financial savings if and when appropriate environmental legislation is in place. Therefore, this research presented in this thesis will document the energy and environmental savings produced together with the economic benefits of each system.

Chapter 4

Two-Unit Model

4.1 Introduction

Decisions concerning whether or not to adopt the CHP option in the UK tend to be dictated by a single factor, the pay-back period. While there are other criteria that influence the decision, this is usually the over-riding one. This investigation will assess the operational behaviour of two CHP units (i.e. the heat and power outputs, operational hours, part-load operation hours and pay-back period) in order to determine if there are any economic or operational benefits from two units over-and-above those achieved with a single CHP unit.

4.2 The Two-Unit Model

Evaluating the relative economics of prospective CHP systems is complicated and time consuming. To try to optimise the choice, a mathematical model of the performance of the system and an associated computer program were constructed. The model has been used to assess the behaviour of twelve packaged gas-fired spark-ignition CHP units. The electrical outputs of the units used, together with capital and running costs as well as fuel inputs - is given in Table 4.1. Budget costs have been used for the capital and installation costs of the CHP systems. Each application for CHP will usually require different installation arrangements but for simplicity, it has been assumed that the installation procedure will be identical for each site.

It is proposed that a primary CHP unit satisfies the base heat load and a secondary unit meets the peak load. The second CHP unit must possess the ability to modulate its electrical and heat output down to 50% of maximum outputs; below which it is not usually financially viable to operate the unit.

For this investigation, manufacturers of small-scale CHP units were consulted in order to determine the performances of their units with modulated outputs. The information gathered is given in Figures 4.1 and 4.3, which along with Table 4.1 forms the input data for the computer program. A flowchart for the operation of the computer program can be found in Figure 4.2.

ELECTRICITY OUTPUT (kW_e)	RATE OF HEAT OUTPUT (kW_T)	RATE OF FUEL INPUT (kWh/hour)	CAPITAL COST (£)	MAINTENANCE COST (p/kW)
32	54.4	116	40000	1.13
48	90	171	52000	1.00
70	114	250	65000	1.00
110	171	400	80000	1.00
150	226	510	90000	0.95
200	324	669	110000	0.90
220	343	800	118800	0.90
255	414	854	135000	0.85
385	641	1313	197500	0.80
507	728	1782	255000	0.70
762	1049	2608	380000	0.70
1025	1423	3506	510000	0.70

Table 4.1: CHP unit specifications and estimated costs [26].

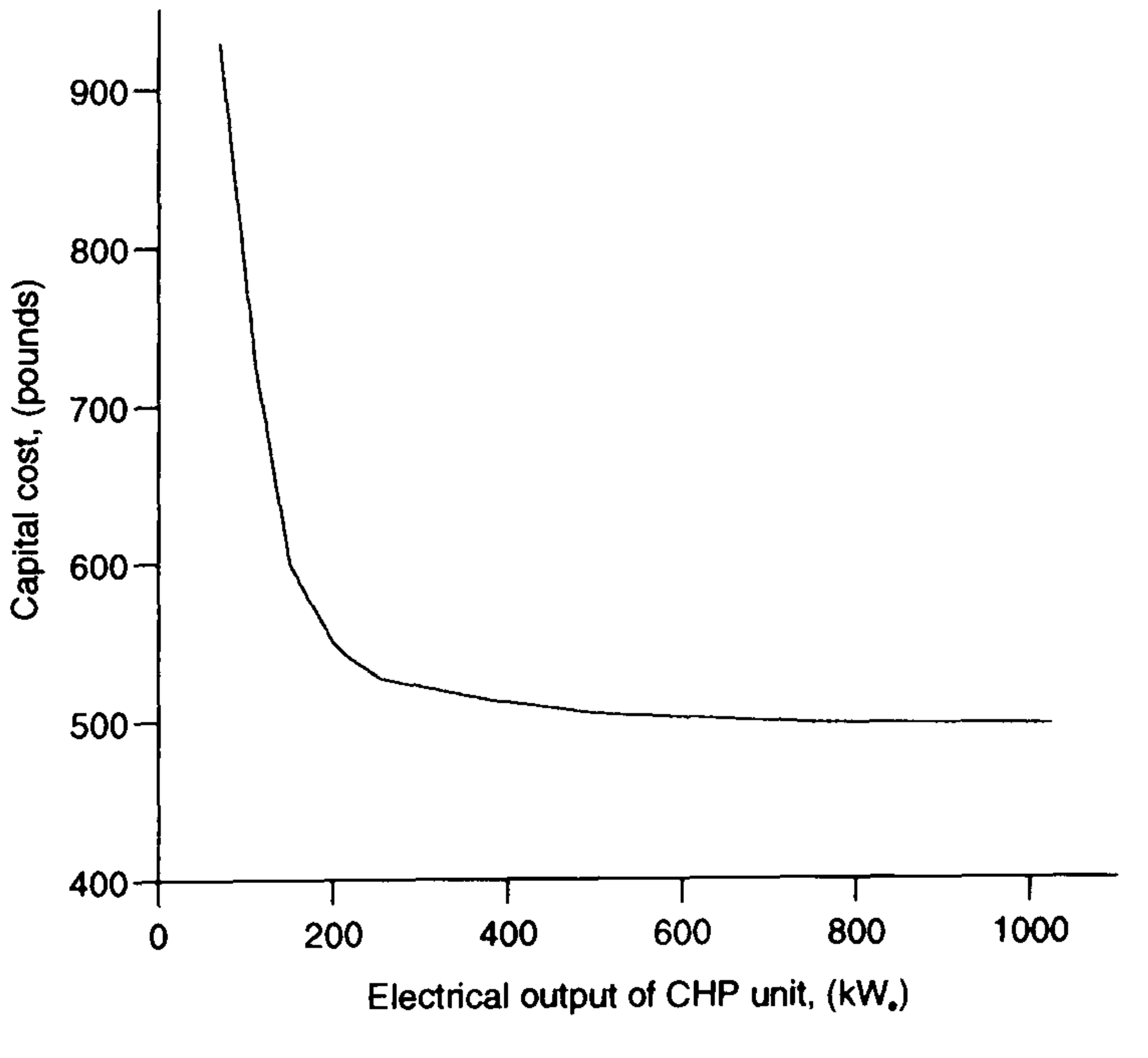


Figure 4.1: Capital cost/kW_e for the 12 off-the-shelf CHP units.

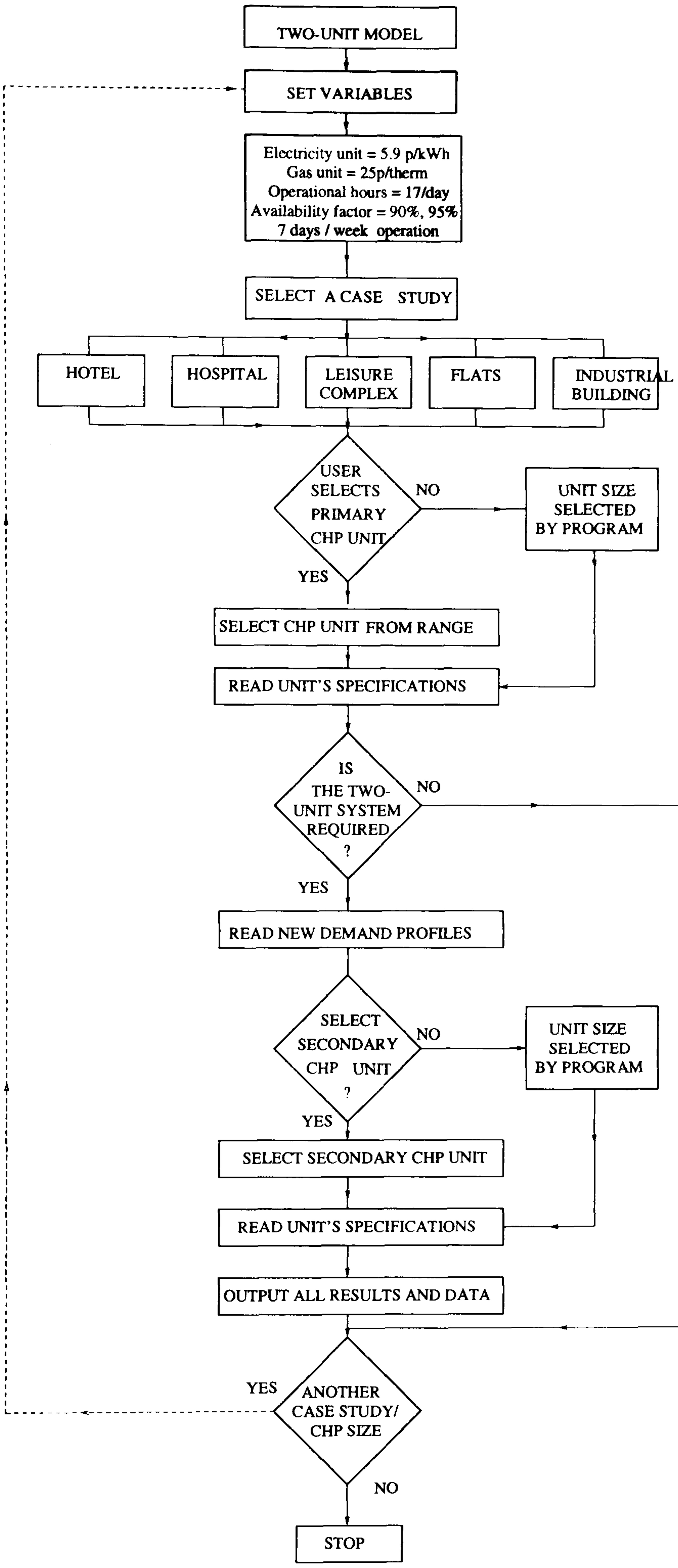


Figure 4.2: Flowchart for describing the behaviour of the two-unit CHP model.

The CHP units will be required to modulate their output at times of reduced demand for energy. The two-unit model simulates the part-load performance of the CHP units according to the performance illustrated in Figure 4.3.

As the CHP unit's output is modulated the electrical efficiency decreases, whereas, the thermal efficiency increases because the heat-output does not decrease at the same rate as the electrical output.

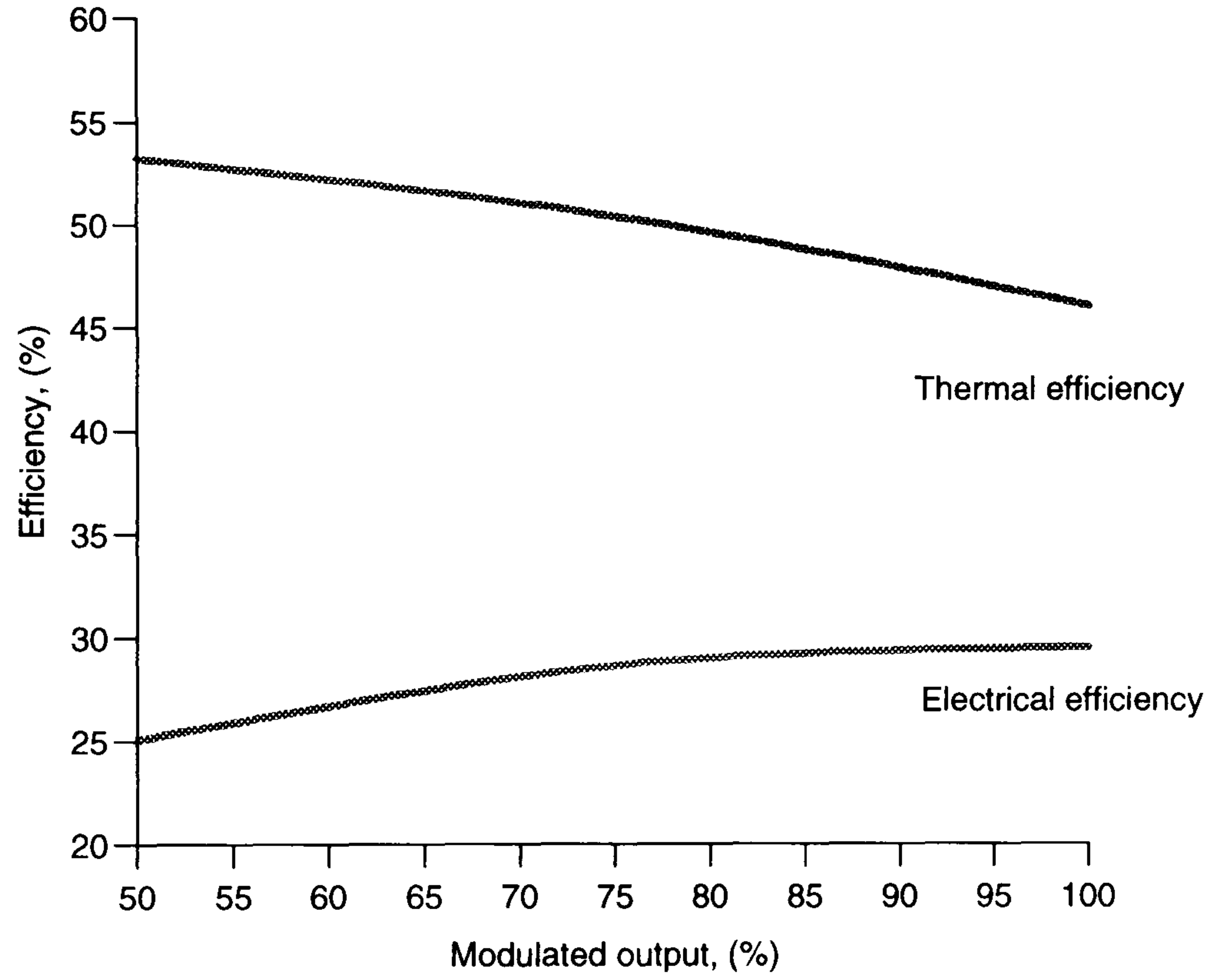


Figure 4.3: Average part-load performances of typical small-scale CHP units.

The mathematical model describing the performance of the two-unit system examines the pay-back periods for the two separate CHP units, which, when installed, satisfy five different demand-scenarios. The pay-back period achieved for the two-unit model can then be compared with the pay-back periods obtained for a single CHP unit. The total electrical outputs of the two-unit system are compared in each case with that from the single CHP unit.

4.3 The Case Studies

Five different prospective applications (extracted from reference [12]) were assessed:

- HOTEL
- HOSPITAL
- LEISURE COMPLEX
- BLOCK OF FLATS
- INDUSTRIAL BUILDING

These represent a cross section of commonly-encountered applications for CHP in the United Kingdom. This heat and electricity demand-profiles are examined for January and July for each site displayed in Figures 4.5→4.9. Figure 4.4 summarises the heat-to-power demand ratio for each site. Note that in practice care must be taken when making predictions as geographical differences in their exact locations can produce significant temporal and climatic variations, which might vitiate any generalised conclusions.

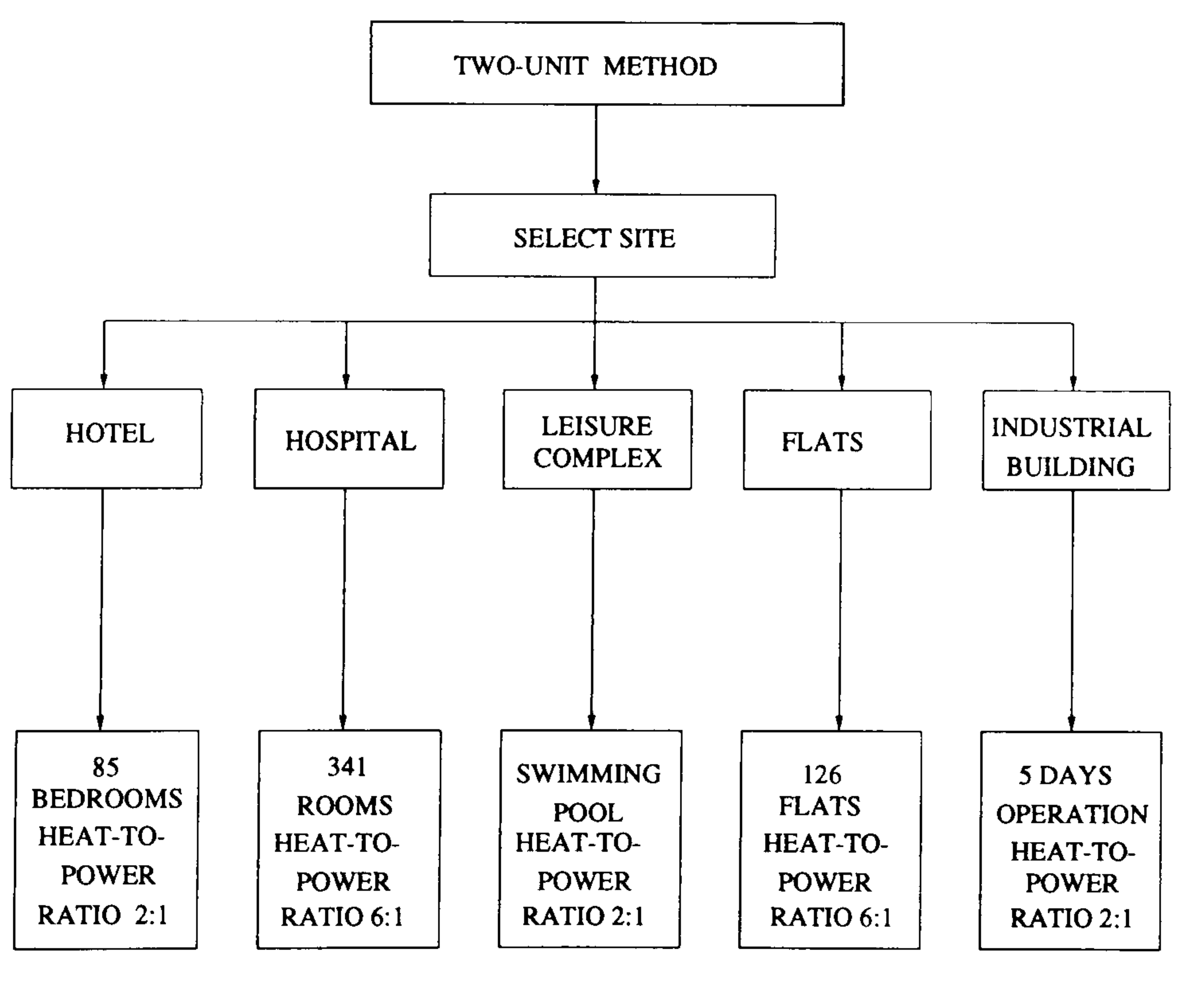


Figure 4.4: Summary of the five case studies selected.

The hospital has an almost constant demand for electricity throughout the year (see Figure 4.6). The industrial building has a greater demand for electricity in

July than in January (see Figure 4.9), because of numerous refrigeration units employed on site. It was not possible to obtain detailed heat-and-electricity demand information for every case, and therefore the profiles for the industrial building and the leisure complex (see Figures 4.7 and 4.9) were estimated with the aid of quarterly fuel bills.

The cases considered take advantage of the low unit-price of electricity available at off-peak times from the national grid. This means that the CHP units will run for only seventeen hours/day. However, with the exception of the industrial building, the demand requirements will ensue for twenty-four hours each day, seven days per week. The industrial building operates for only eight hours each day and on a five-day per week basis.

4.3.1 The Hotel

Hotels tend to have relatively high levels of heat-and-power demands, especially those utilised for the conference trade or if a heated swimming pool is provided. The hotel investigated in this study contains 85 bedrooms and several public spaces (making it a suitable venue for conferences and other large functions), but it has no swimming-pool [12]. Its residents require space heating and hot water for washing - see Figure 4.5. Electricity is used for lighting, cooking, air conditioning and operating television sets and kettles. The hotel has an average heat-to-power demand ratio of 2:1.

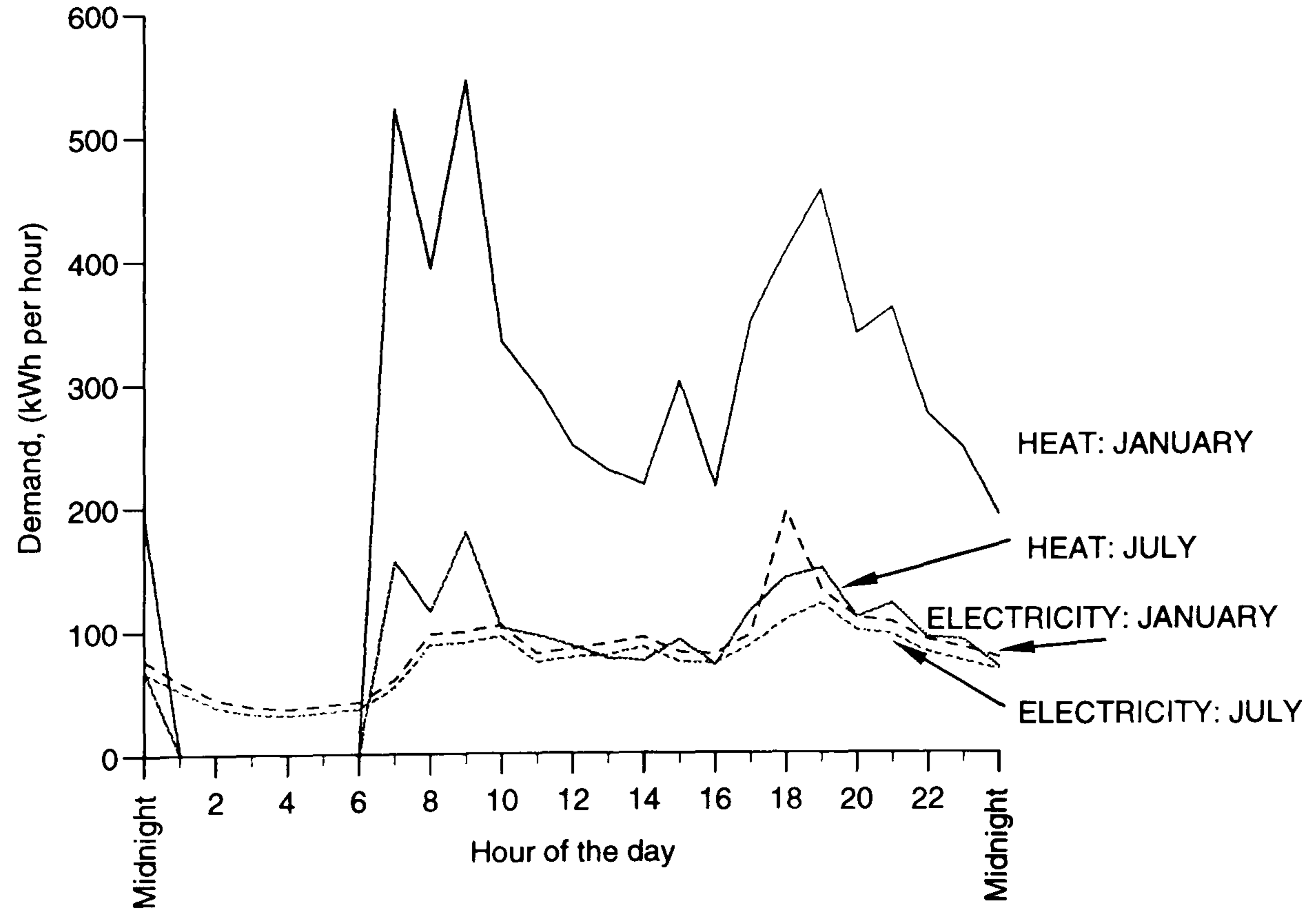


Figure 4.5: Heat-and-electricity demand-profiles for the hotel.

4.3.2 The Hospital

This has 361 rooms and an average heat-to-power demand ratio of 6:1. It exhibits a mixed residential/industrial energy-demand pattern. The wards and staff accommodation units represent the residential aspect, and the laundry and related service activities the industrial part [12]. As hospitals tend to operate continuously, they tend to be financially-attractive propositions for the installation of CHP units - see Figure 4.6.

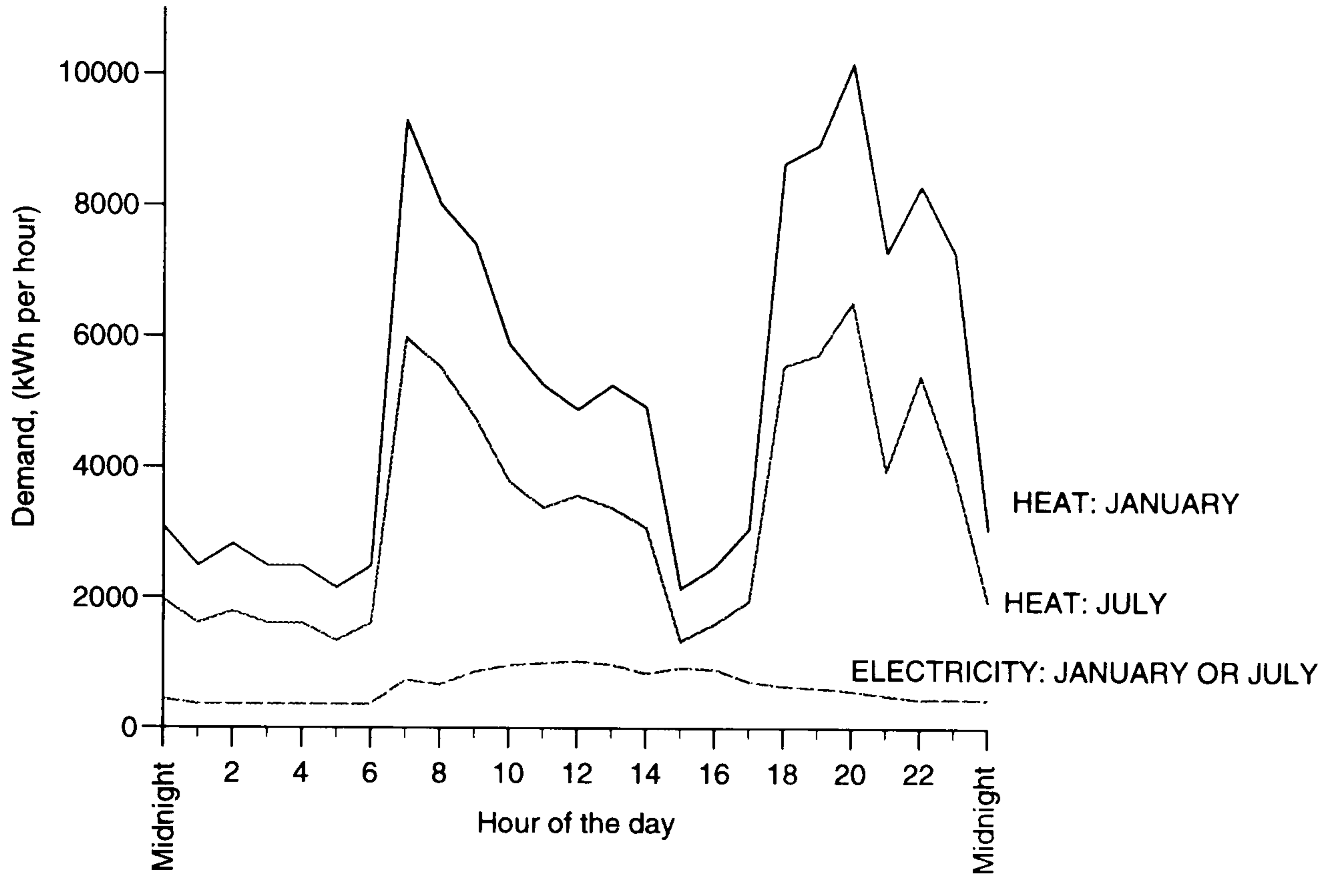


Figure 4.6: Hospital: Heat and electricity demand-profiles.

4.3.3 Leisure Complex

Leisure complexes are often run by local authorities. If a swimming pools is included on the site the use of CHP can be particularly attractive. The investigated complex has the following energy requirements [12] -

1. Heating the swimming pool and hot water for the showers; these represent most of the energy demand and only vary slightly seasonally. A substantial summer heating-load exists, which is uncharacteristic for many other sites.

2. The electricity demand is associated mainly with lighting and the operation of pumps. This daily demand is almost steady throughout the year - see Figure 4.7.

3. The complex has an average heat to electric-power demand of 2:1.

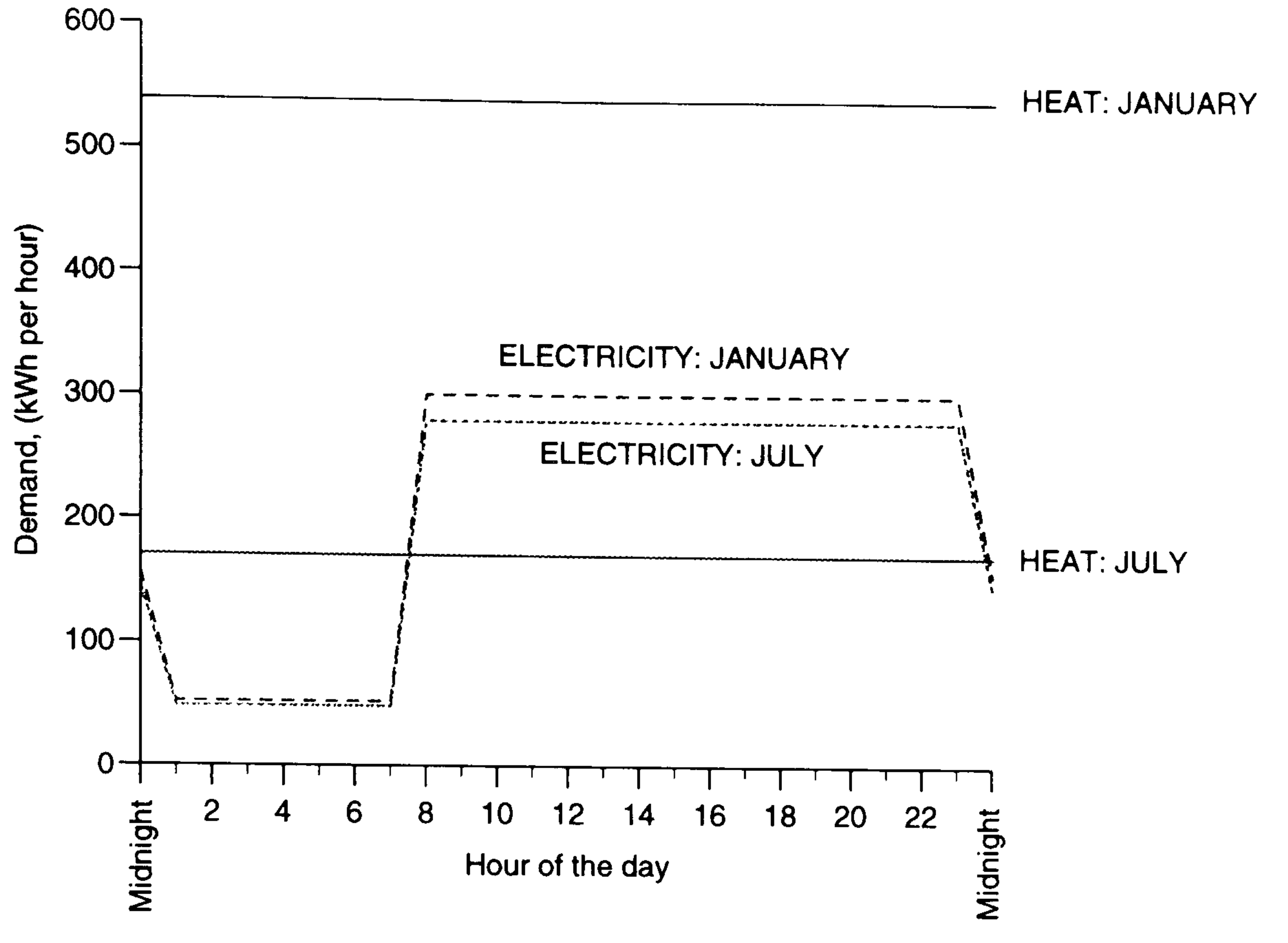


Figure 4.7: Leisure Complex: Heat and electricity demand-profiles.

4.3.4 Residential Block of Flats

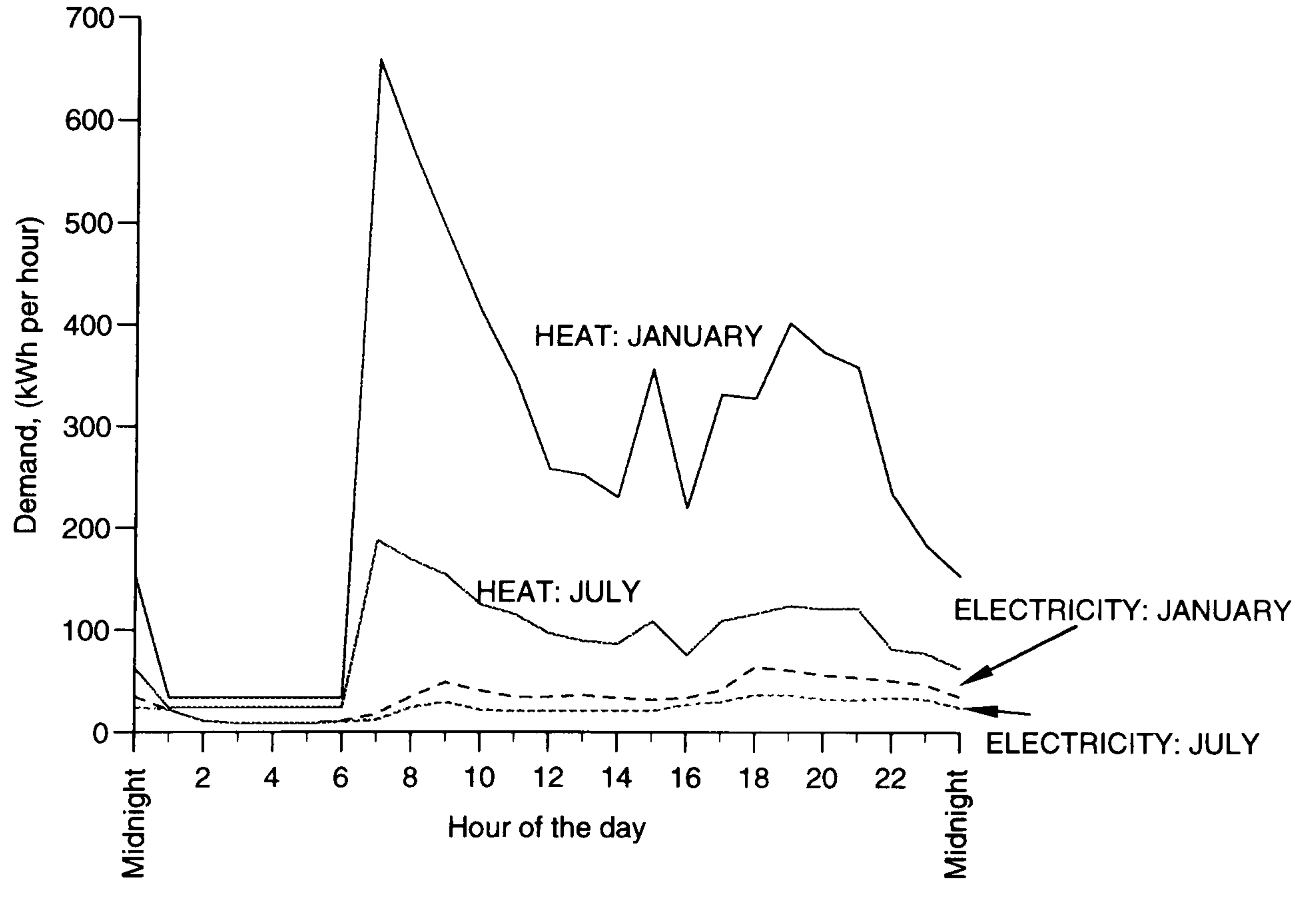


Figure 4.8: Block of flats: Heat and electricity demand-profiles [12].

The high-rise block of flats examined in this case study contains 126 separate apartments [12], and has an average heat-to-power demand ratio of 6:1 - see Figure 4.8.

4.3.5 Industrial Building

A slaughterhouse is chosen for this study: it has two main energy requirements:-

1. A supply of hot water at 80^o C or more, for cleaning and sterilising.

2. Electricity to drive the refrigeration plant.

The monthly total energy-demand is almost constant throughout the year - see Figure 4.9. The hot-water requirement fluctuates widely during each day and is typically supplied from steam-heated calorifiers which store the hot water. The heat demand is practically zero outside normal working-hours (i.e. at night and week-ends). The electricity demand, which is associated mainly with the operation of the refrigeration plant, is relatively steady throughout the year, including week-ends [12].

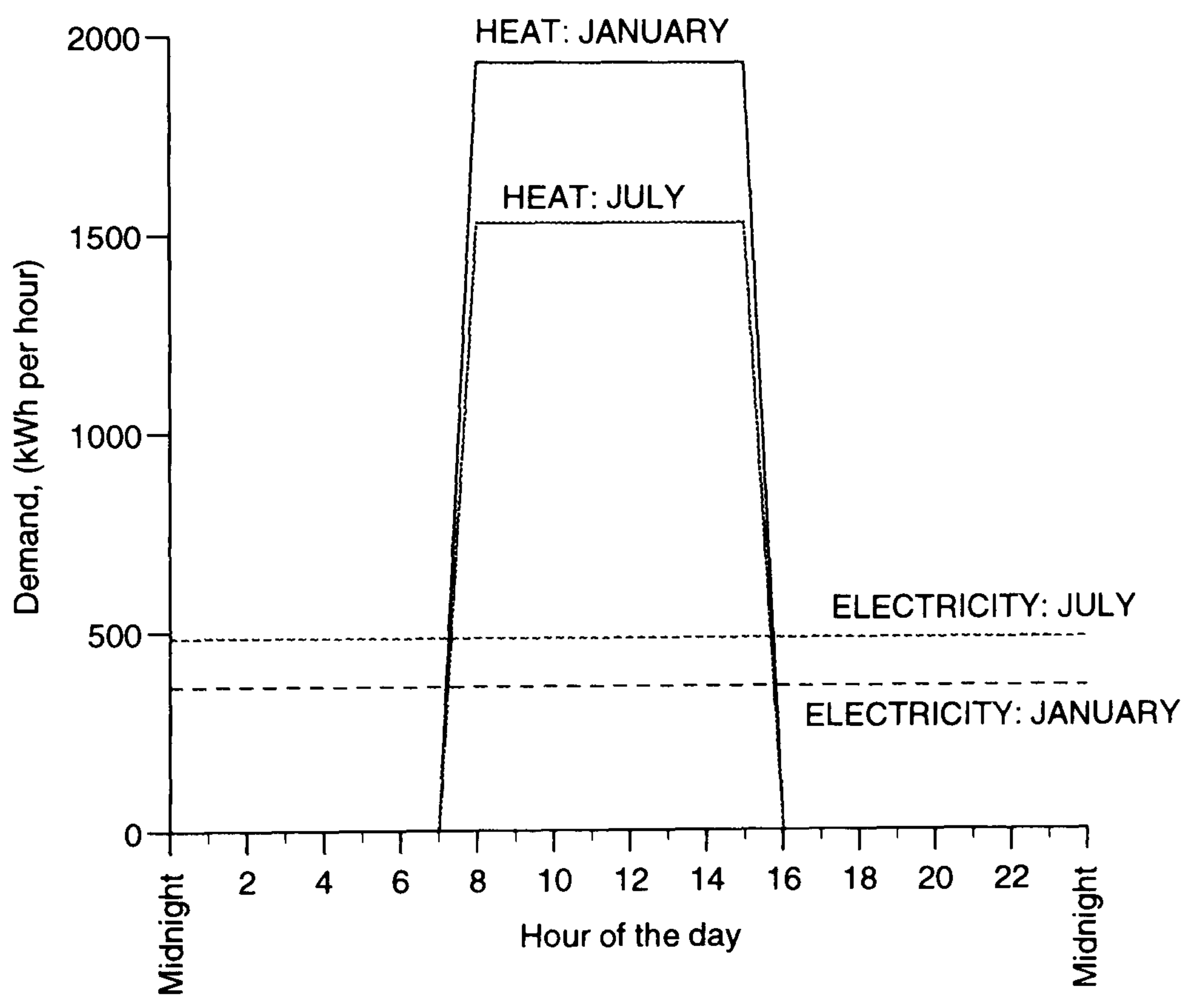


Figure 4.9: Industrial Building: Heat and electricity demand-profiles.

4.4 Predictions

The mathematical-model was applied to the five case studies. The number of operational hours and predicted simple pay-back periods for the single and double CHP units used are presented in Tables 4.2 and 4.3 respectively.

CASE STUDY	ELECTRICAL POWER OUTPUT (kW_e)	HEAT OUTPUT (kW_T)	NUMBER OF RUNNING HOURS (per year)	SIMPLE PAY-BACK PERIOD (years)
HOTEL	70	114	6174	4.41
	110	171	5803	4.77
HOSPITAL	507	728	6205	2.19
	762	1049	6205	2.51
LEISURE COMPLEX	220	343	5678	3.20
	255	414	5151	3.08
BLOCK OF FLATS	32	54.4	6205	7.08
	48	90	6205	7.64
INDUSTRIAL BUILDING	255	414	2085	5.58
	385	641	2085	5.60

Table 4.2: Characteristics of the single-unit CHP systems for the five different applications (AF=90%)

When the CHP units installed at the hotel, hospital, leisure complex and block of flats are running for a maximum of 17 hours per day, 7 days per week, the total number of running hours over one-year is 6,205. In the case of the industrial site, which has a demand for energy for 5 days per week, the maximum total number of running hours per year is 4,432. However, as the demand for heat for the industrial building ensues only between 7am and 4pm, the CHP unit will not be operated at other times and consequently the number of operational hours for the year is limited to 2085.

The CHP units used for all the case studies will have a continuous running life of approximately ten years for the stated operational period. If the running hours are less than 6,205 per year, then each unit's life will appropriately exceed ten years. This will be significant when making comparisons between financial options for the two systems since the life expectancies of the primary and secondary units will influence the overall evaluation.

CASE STUDY	SIZE (kW_e)			NUMBER OF RUNNING HOURS (per year)		SIMPLE PAY-BACK PERIOD (years)	
	A	B	Total	A	B	(AF=0.90)	(AF=0.95)
HOTEL	48	32	80	6205	4948	5.47	5.20
	70	48	118	6174	3788	6.08	5.80
HOSPITAL	385	150	535	6205	6205	2.28	2.17
	507	255	762	6205	6205	2.54	2.41
LEISURE COMPLEX	150	70	220	6205	4733	3.72	3.55
	220	48	268	5678	4253	3.93	3.75
BLOCK OF FLATS	32	32	64	6205	5837	15.16	14.54
INDUSTRIAL BUILDING	150	110	260	2085	2085	7.42	7.11
	200	200	400	2085	2085	6.31	6.04

Table 4.3: Characteristics of the two-unit CHP systems for the five applications.

Selection Procedure for CHP Systems

Two differently-sized single-unit CHP systems have been selected for comparison with the two-unit systems for each of the case studies except the flats (which only has one practical two-unit combination). The smaller single-unit system is intended to represent sizing below the base heat-load, whilst the larger single-unit system corresponds to a point above the base load. This approach is required because CHP units are only commercially-available in discrete sizes. Therefore, it is not usually possible to find a unit which exactly matches the energy-demand for any site. In the cases of the hospital and the block of flats, the single units used have been sized below the base heat-load because of their substantially higher heat-to-power demand-ratios, which would result in the export of large amounts of electricity. However, Commercial practices in the UK mean that exporting electricity to the national grid is poorly rewarded per kWh compared with the cost per kWh for purchasing from the grid and this is not usually regarded as economically viable. When a two-unit system was chosen to be employed, to wholly or partially satisfy the energy demands for each of the case studies, two selection criteria had to be satisfied:-

1. The total combined electrical output from the two units had to equal approximately the electrical output produced by the single-unit system.

2. The two-unit combination providing a pay-back period, which is either shorter than or nearer to that of the single unit, was selected.

In Table 4.3 the number of hours per year for which the primary and secondary CHP units operate has been predicted. Note that the operational hours are less for the secondary unit than for the primary unit in the cases of the hotel, leisure complex and flats.

4.4.1 Observations

The pay-back periods for the single CHP unit are shown in Table 4.2 and have been predicted using an availability factor of 90% based on the number of running hours for each CHP unit. In the case of the two-unit system, each CHP unit is assumed to have an availability of 90%. However, the overall availability of the system is now assumed to be 95% and the predictions are shown in Table 4.3. Pay-back periods have also been included for an availability of 90% for comparison purposes. As the likelihood of the two CHP units failing simultaneously is very small, a higher availability factor has been used in the latter case, leading to a reduction of the pay-back periods for all the considered cases. In the event of one unit failing or undergoing routine maintenance, the other unit would be able to maintain a reduced supply of both heat and electricity. Note, however, that high availability factors can only be achieved consistently through extensive and regularly-undertaken maintenance programmes.

4.5 Comparisons of Pay-back Periods

In each case-study the performance of a two-unit system has been compared with that of a single CHP unit - see Table 4.4 for the specific combinations under investigation. These cases were selected since they offered pay-back periods which were nearest to those for the single CHP unit.

CASE STUDY	SINGLE-UNIT		TWO-UNIT	
	OUTPUT (kW_e)	PAY-BACK PERIOD	OUTPUT (kW_e)	PAY-BACK PERIOD
HOTEL:	70	4.41	48+32	5.20
HOSPITAL:	762	2.51	507+255	2.41
LEISURE COMPLEX:	255	3.08	220+48	3.75
BLOCK OF FLATS:	48	7.64	32+32	14.54
INDUSTRIAL BUILDING:	385	5.60	200+200	6.04

Table 4.4: Two-unit CHP combinations selected for comparison and their respective pay-back periods.

Employment of the two-unit system does not achieve shorter pay-back periods than those obtained with the single-unit system for any of the cases studied when the availabilities of each system are taken as 90%. The case of the 507+255 kW_e units installed at the hospital produced the least difference in pay-back periods between the single and double-unit systems, with an increase of less than one month. In the cases of the industrial building, leisure complex, hotel and flats, the pay-back periods for the two-unit system are longer by approximately 9 months, 1 year, 1 year and 7 years respectively. The installation of both the single and double-unit systems at the flats and the industrial building produce unacceptably long pay-back periods. For the case of the flats, this is because the energy demand is too small to require anything larger than a single $32kW_e$ CHP unit, which could not be provided by any combination of two, at present commercially-available, units. The short operating hours at the industrial building are the main reason for the long pay-back periods predicted. The pay-back period for the industrial complex would be shortened significantly if the site operated for more than 5 days/week. The cases of the flats and industrial building will not be considered any further in this study.

95% availability

If an availability of 95% is assumed for the two-unit system, then the pay-back period predicted for the 507+255 kW_e system will decrease, resulting in the prediction of a two-week shorter pay-back period than for the single-unit system. The pay-back periods of each of the other four two-unit systems will also shorten with the leisure complex and hotel now only 8 and 9.5 months longer respectively . However, they are still longer than that predicted for the single unit.

Consideration of the pay-back period alone will not illustrate all of the benefits offered by CHP systems and particularly the two-unit system. Gas and electricity prices are extremely volatile, leading to dramatic changes to the predicted pay-back periods over a short period of time, which may discourage the potential investor in CHP technology. Therefore, this method on its own is not a satisfactory means for appraising all of the benefits offered by the system. Consequently, consideration will now be given to the additional energy and secondary benefits offered by the two-unit system.

4.6 Total Electrical and Heat Outputs

In each of the five cases considered, it is possible to achieve greater electrical and thermal outputs from the installation of the combined system than that produced by the single-unit system used for the comparison. The additional heat and electricity produced will increase financial savings and the displacement of CO_2 emissions, where there exists a demand for the appropriate energy form from the site. However, fuel and maintenance costs will also increase. The two-units will be a worthwhile option to be considered for any future expansion at any of the sites, if need for more heat and power is likely to occur.

Table 4.5 documents the increase in the potential heat and electricity output from the two-unit systems. All of the combinations presented for the two-unit systems in Table 4.5 - with the exception of electricity at the hospital - can produce more heat and electricity than their single-unit counterparts. If this additional energy can be utilised at the site, then further energy, environmental and financial savings will ensue. The systems which are the most effective at utilising this additional energy will produce the greatest savings. Table 4.6 illustrates how effective each combination is at utilising the additional heat and electricity produced by the two-unit system. With the exception of one of the combinations installed at the industrial building, all of the systems utilise some of the additional heat. Each of the two-unit systems will utilise more electricity than the single-unit systems. The exception is the case of the 507+255 kW_e units installed at the hospital, which does not utilise more electricity because there is no additional electricity from this two-unit system and both units operate for the maximum number of hours per year.

CASE STUDY	OUTPUT (kW)				Potential Additional Energy Output by Adopting the Two Rather than the Single-Unit Option, MWh/year, (%)	
	SINGLE UNIT		TWO UNITS			
	Electricity	Heat	Electricity	Heat	Electricity	Heat
Hotel	70	114	80	144.4	62.5 (+14.3%)	188.6 (+26.7%)
Hospital	762	1049	762	1142	0.0 (-)	577.1 (+8.9%)
Leisure Complex	255	414	268	433	80.7 (+5.1%)	117.9 (+4.6%)
Flats	48	90	64	109	99.3 (+33.3%)	117.9 (+21.1%)
Industrial Building	385	641	400	648	66.5 (+3.9%)	31.0 (+1.1%)

Table 4.5: Heat and electric-power outputs for single versus double units, as specified in Table 4.4, and the potential additional savings from adopting the two-unit system.

CASE STUDY	Single-unit System			Two-unit System					
	CHP (kW_e)	Savings, MWh		CHP, kW_e		Savings, MWh			
						Electricity		Heat	
		Electricity	Heat	A	B	Output	% rise	Output	% rise
Hotel	70	411.8	678.2	48	32	445.2	+8.0	810.5	+19.5
	110	520.8	892.7	70	48	537.2	+3.0	991.5	+11.0
Hospital	507	3,110.2	4,517.3	385	150	3,257.3	+4.7	5,379.8	+19.1
	762	4,217.9	6,509.0	507	255	4,218.3	+0.0	7,086.1	+8.9
Leisure	220	1,078.6	1,809.8	150	70	1,162.6	+7.7	1,891.8	+4.5
Complex	255	1.142.8	1,993.2	220	48	1,248.4	+9.2	2,192.6	+10.0
Flats	48	207	550.4	32	32	224.9	+8.6	638.5	+16.0
Industrial	255	531.8	863.5	150	110	542.3	+1.9	828.1	-(4.1)
Building	385	772.9	1,337.0	200	200	783.4	+1.3	1,351.5	+1.0

Table 4.6: Comparison of heat and electricity outputs for the two systems at the five sites.

4.7 General observations.

The pay-back period achieved with the 507+255 kW_e two-unit system installed at the hospital for an availability of 95% is shorter than that produced for the single-unit CHP system (availability 90%). This is achieved without the need for the inclusion of maintenance cost reduction or the export of surplus electricity. When the data from the two-units is examined in detail for each case more reasons for the achievement of shorter pay-back periods emerge:

Annual running and total capital costs for the system increased by 2.2% and 2.6% respectively and heat output is up 577 MWh. The value of this heat (allowing for additional running costs) will contribute towards the reduction of the pay-back period. The use of two CHP units in place of one at the hospital did not allow operational benefits in terms of increased energy utilisation. The significant factor in this case - relating to the prediction of a shorter pay-back period - is the assumption of increased availability for the two units.

CASE STUDY	RUNNING COST	CAPITAL COST	ELECTRICITY OUTPUT		HEAT OUTPUT	
			Potential	Actual	Potential	Actual
HOTEL	+8%	+42%	14.3%	8.0%	26.7%	19.5%
HOSPITAL	+2.2 %	+2.6%	0%	0%	8.9%	8.9%
LEISURE COMPLEX	+19.8%	+26%	5.1%	9.2%	4.6%	10.0%
FLATS	+34.3%	+54%	33.3%	8.6%	21.1%	16.0%
INDUSTRIAL BUILDING	+5.1%	11.4 %	3.9%	1.3%	1.1%	1.0%

Table 4.7: Predicted excess (as a percentage of the corresponding parameter for the single-unit system) for the two-unit system.

Results in Table 4.7 indicate that the leisure complex appears to consume more heat and electricity from the two-unit system than can be accounted for by the predicted rise in energy output alone. Detailed analyses of the data for the electricity and heat generated show an increase in produced electricity and heat, above those from the single unit by 9.2 and 10.0% respectively. The installation of the two-units allows the leisure complex to utilise an additional 105.6MWh of electricity and 199.3MWh of heat each year. The reason for the utilisation of more electricity and heat - than can be accounted for by the rise in potential output alone - is that the CHP unit will not be shut-down as much because of insufficient heat demand, thus allowing the unit to operate for a greater number of hours. The two units in combination now provide a better energy match with the electricity and heat demands at the leisure complex. The additional 13 kW_e (i.e. 5.1% greater than the single-unit's electrical output) and 19 kW_T (i.e. 4.6% greater than the single-unit's heat output), produced and utilised, will lead to financial savings of over £6.100 per year above that obtained with the single unit if all of the energy provided is utilised. The theoretical increase in running costs for the two-unit system, over-and-above that of the single 255 kW_e unit, is £7,446 (80.7MWh_e & 117.9MWh_T), thus indicating a loss of over £1,300. Analysis of the predictions from the model indicate that the actual increase in heat and electricity consumed at the site will provide additional annual savings of £8,498 (105.6MWh_e & 199.4MWh_T) for a cost of £9,251, producing a annual loss of £753. Increased fuel consumption and proportionally higher maintenance costs are the main causes of this operational loss. The two-unit system can offer increased heat and electricity utilisation from the CHP units at the site. However, the economic value of this energy is less that the cost incurred to produce it. The dramatic increase in capital costs (+26%) and running costs (+19.8%) for the two units in the case of the leisure complex form another factor in the prediction of a longer pay-back period.

In the case of the hotel the additional potential heat and electricity output from the two-unit system is not utilised. This combined with a 42% increase in capital costs ensures that the 48+32 kW_e system will fail to produce a shorter pay-back period than the single 70 kW_e unit. .

4.7.1 Reduced maintenance costs

In the economic evaluation of the two-unit system, the appropriate charge for the maintenance cost of each CHP unit has been selected at the full rate. No allowance has been made for the possibility of reducing maintenance costs when both units are serviced simultaneously, reducing the number of visits that an engineer might have to make to the site during the year. The computer program was re-run for each two-unit system with maintenance charges reduced by 10% (established as an appropriate approximation after consultation with industry specialists) - see Table 4.8. Consequently, all of the pay-back periods for the two-unit system are reduced further.

4.7.2 Electricity and heat export

The greater electrical and heat outputs produced by the two-unit system will produce additional economic savings when the energy is required at the site. However, if there is a short-term excess of electricity and/or heat, then either export or storage options can be considered.

CASE STUDY	SINGLE CHP UNIT		DOUBLE CHP UNIT	
	OUTPUT (kW_e)	PAY-BACK PERIOD (years)	TWO-UNIT OUTPUT (kW_e)	PAY-BACK PERIOD (years)
HOTEL	70	4.41	48+32	5.07
HOSPITAL	762	2.51	507+255	2.37
LEISURE COMPLEX	255	3.08	220+48	3.65

Table 4.8: Pay-back periods for the two-unit system when reduced maintenance costs have been included.

Export of electricity

Surplus electricity produced by the two units could be sold to the grid, slightly improving the overall economics. Until recently the very low prices paid per kWh have discouraged this practice. Table 4.9 summarises the predictions under these circumstances. Where it is possible to export electricity to the grid, unit prices now vary from 2 to 3p/kWh with an average taken at about 2.5p/kWh. Using this average value for the exported electricity, revised pay-back periods can be obtained for the single and two units employed at the five sites. In each of the cases and for both the single and two-unit systems, the availability of electricity for export produces a further reduction in the pay-back period. In the case of the hospital the advantage of the two-unit system has decreased because of the quantity of electricity available for export from the single 762 kW_e unit. The storage of electricity will not be considered in this study.

CASE STUDY	SINGLE CHP UNIT		DOUBLE CHP UNIT	
	OUTPUT (kW_e)	PAY-BACK PERIOD (years)	TWO-UNIT OUTPUT (kW_e)	PAY-BACK PERIOD (years)
HOTEL	70	4.17	48+32	5.06
HOSPITAL	762	2.22	507+255	2.20
LEISURE COMPLEX	255	2.77	220+48	3.43

Table 4.9: Pay-back periods for the two-unit system when the export of electricity has been included.

Export or storage of heat

Throughout this study the model has simulated CHP modulation on heat-demand for the five sites, therefore, no excess heat will be available for export or storage. If this arrangement is changed to allow the CHP units to modulate their output on electricity-demand or without modulation at all, then excess heat will become available. The potential for integrating CHP and energy storage is considered in greater detail in Chapter 5. The export of heat will not be considered in this study.

4.7.3 Analysis of Operational Hours

With the exception of the combinations installed in the hospital and industrial building, all the secondary units shown in Table 4.3 run for less than 100% of their potential operational hours. Thus the operational life of the second unit will exceed that of the primary unit. If this is accounted for in the economic evaluation of the CHP system, then the adoption of a two-unit system becomes even more attractive. Consider the case of the hotel with a single 70 kW_e unit, which will have a pay-back of 4.41 years. The two-unit system has a longer pay-back of 5.20 years. However, at the end of the pay-back period, the second unit will have been running for only 80% of its estimated lifetime and of the single 70kW_e unit's lifetime. If the calculations are reworked, taking the capital cost of the secondary unit at 80% of its actual cost in order to reflect the unused part of the expected lifetime of the secondary unit, then a shorter pay-back period of 4.75 years (only 4 months greater than the single unit's pay-back period) would result. If the same approach is taken for the leisure complex - 220+48 kW_e system, then the resulting pay-back period will be 3.55 years, producing a pay-back period for the two-unit system which is approximately six-months longer than that for the single unit. A summary of the effect on the pay-back periods for each of the five systems is presented in Table 4.10.

	Single-unit System			Two-unit System				
	CHP Size, kW_e	Pay-back years	Operating hours	CHP Sizes A+B kW_e	Secondary Unit hours	Secondary Unit %	Pay-back period Old	Pay-back period New
Hotel	70	4.41	58036174	48+32	4948	80	5.20	4.75
Hospital	762	2.51	6205	507+255	6205	100	2.41	2.41
Leisure Complex	255	3.08	5151	220+48	4253	83	3.75	3.55
Flats	48	7.64	6205	32+32	5837	94	14.54	14.10
Industrial Building	385	5.60	2085	200+200	2085	100	6.04	6.04

Table 4.10: Pay-back periods for a reduced capital cost for the secondary CHP unit

The general advantages and disadvantages in employing the double-unit system can be summarised as follows:

Advantages

1. Pay-back periods can be shorter for specific conditions.
2. Back-up from the second unit is available during periods of break-down or for servicing.
3. Increased availability of heat and electricity output.
4. Enhanced flexibility permits increased electrical and heat outputs and can provide the site with a more appropriately matched supply of energy.
5. The secondary unit can have a longer life because of its lower rate of use per year. This should lead to only a staggered further investment being required after the initial capital outlay.

Disadvantages

1. Capital cost will usually be higher.
2. Maintenance and fuel costs are proportionally higher for smaller CHP units.
3. The results are heavily dependent on the modulation capability and the performance of the secondary CHP unit.
4. The additional CHP unit will require more space on site.

4.7.4 Limitations and Future work

The investigation undertaken here represents an appraisal of the performance of the double-unit system when compared with that of the single-unit system. Because of this comparative approach, demand and tariff structures have been simplified. Future research should include the use of more detailed energy-demand profiles. The economic predictions which have been produced are dependent on the supplied specifications and costs, for the commercially-available CHP units and the current unit prices of electricity and gas, which have been extremely volatile since the privatisation of their respective industries. Also the capital costs (including installation costs) employed in this model are budget figures only. These can vary significantly between manufacturers, or if the specifications for heat distribution at a site are complex. The predicted economic results from the model are sensitive to any variation of this data. If the range of available CHP units is expanded, it is possible that all of the pay-back periods for each system could be reduced further, because the number of combinations of small-scale CHP unit sizes commercially-available become greater.

The study to date relies heavily on the effectiveness of modulation of the secondary unit's output and it is important to account for the reduction in efficiency which will accompany the modulated operation. Therefore it was necessary to determine the sensitivity of the predictions from the model to variations of the fuel efficiency resulting from being operated on part load. It was found that a 10% reduction in the fuel-efficiency factor led to a 1% reduction in the pay-back period. This was not considered significant for the combinations and case studies documented in this investigation.

4.8 Conclusions

A comparative study has been undertaken into the potential benefits of installing two smaller CHP units in place of a single larger unit at five test sites. It is possible, for one of the case-studies considered, to achieve a shorter pay-back period when using the double-unit rather than the single-unit system. In particular, the 507+255 kW_e CHP installation at the hospital leads to the prediction of a one-month shorter pay-back period for the two-unit system with 95% availability. In the other two cases (where CHP is considered as a viable economic option), longer pay-back periods ensue by the installation of the two-unit rather than the single-unit system. However, a shorter pay-back period for the two-units is only achieved through the assumption of a higher availability (i.e. namely 95%) for the two-unit system, against 90% for the single-unit system. The operation of the two-unit system at the leisure complex illustrated how energy-utilisation can be increased to above that of the single CHP unit. However, the system is still not economically viable in this case. Pay-back periods are reduced further when allowances are made for maintenance cost reductions and the export of surplus electricity, although the single unit remains the most economically attractive in all cases except that of the hospital.

Achieving a significantly shorter pay-back period would be a great incentive for any potential investor in CHP. However, the study indicated that this is not achievable for the majority of the cases considered. It is possible that many of the other benefits of the two-unit system suggested could also influence favourably the investor. For example, the availability of the second unit for back-up in the case of breakdown or servicing could be a major consideration, if security of supply is essential. In these cases, the value of the secondary CHP unit could be significant to a company because of the high cost of a complete shut-down or shortfall of electricity and heat at a site. The two-unit system can offer increased protection from this expensive eventuality.

Chapter 5

Integrated CHP and Thermal-Energy Storage

Introduction

The benefits of energy-efficient combined heat-and-power have been stated on several occasions. One of the obstacles to the wider implementation of the technology is the inability to synchronise the intermittent demand for heat and power at the site, with the near constant supply of energy from the CHP unit. If the demand is not simultaneous, then the heat must be dumped or the electrical and heat-output from the CHP unit modulated. Neither of these options are attractive because decreasing the electricity output will reduce the economic savings produced by the CHP unit and dumping heat goes against the aims of those concerned with energy-thrift. An alternative strategy is to store the heat produced by the CHP unit at one point in time and then utilise it on demand at a later time. This chapter will examine the potential for an integrated small-scale CHP and Thermal-Energy Storage (TES) system. An overview of the relevant energy-storage technology will be presented before the technical, environmental and economic aspects of the integrated system are appraised. A predictive model, which was developed to simulate the potential for energy storage, is applied to a variety of test sites. Finally, an industrial application of an operational integrated small-scale CHP/TES system is presented.

5.1 Thermal-Energy Storage

Thermal-energy storage is common. If the requirement is for electrical or mechanical energy, then it may be preferable to store in a higher form. For each kWh of electrical/mechanical energy required, several kWh of thermal-energy must be stored [80].

The need for storage arises on account of our inability to regulate (or maintain constant) our energy demands in relation to our energy supplies. For human activities, the demands usually follow a di-urnal (daily) cycle, although there may be perturbations brought about by local conditions (e.g. an unusually hot or cold day or a national holiday). Industrial processes, generally, have a fairly predictable (though still variable) demand. Air-conditioning demands to provide human comfort are particularly variable and, above all, intermittent. Power supplies - such as that provided by CHP - operate most efficiently and economically at constant load.

The concept of energy storage is well established and has been used in the design and operation of occupied spaces for centuries. A well documented example of the early employment of the technology can be found in the design and construction of the 17th century Taj Mahal, which included the use of energy storage in order to increase the energy efficiency and building comfort. The building incorporated materials with high thermal masses to bridge the gap between the extreme day and night time temperature swings in the local climate throughout the year.

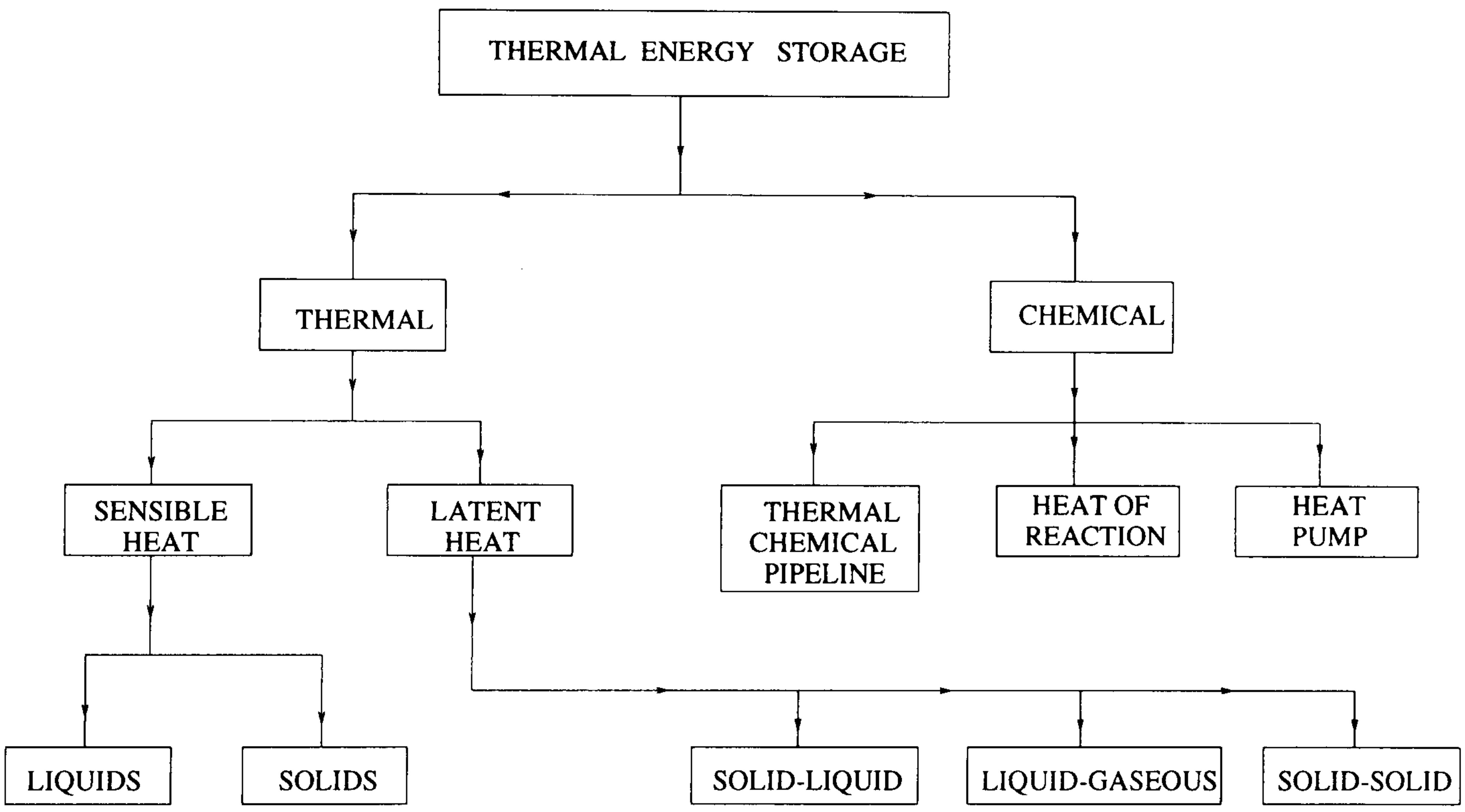


Figure 5.1: Flowchart for energy storage options.

Employing energy-storage systems can, under the right circumstances, increase a systems energy-utilisation efficiency. There are numerous forms of energy-storage including:- mechanical and electromagnetic storage; fossil and direct biomass technologies; chemical, electrochemical and nuclear techniques; as well as the use of the heat capacities of suitable materials. Direct storage of heat in insulated liquids or solids is attainable at comparatively low temperatures, but energy can only be recovered effectively as heat [81]. TES is ideally suited for applications such as space or water heating, where low quality, low temperature energy is required.

Thermal-Energy Storage: in the form of heat, can be defined as the charging and de-charging of a store of finite thermal-capacity in response to the flow of heat to or from a system with both a supply and demand for heat which are out-of-phase. Where the store normally operates as a source of heat, it is known as heat-storage and where it acts as a sink it is known as cool-storage.

The basic modes of thermal-energy utilised in TES systems and considered in this study are sensible-heat and latent-heat [82].

5.1.1 Sensible-Heat Storage

The simplest form of heat-store is an inert body, whose temperature is raised when heat is absorbed and lowered when heat is withdrawn: this is termed sensible-heat storage. The heat-storage capacity of the store will be proportional to the heat-capacity of the storage medium. The heat-capacity of storage mediums is generally relatively low. Therefore, a large quantity of the material will usually be required for commercial applications. The sensible-heat gained or lost by a medium in changing temperature from T_1 to T_2 is given in equations (5.1) & (5.2).

$$Q = m \int_{T_2}^{T_1} C_p \Delta T \, dT \tag{5.1}$$

where: m = mass of storage medium (kg), ΔT is change in temperature (K) and C_p is specific-heat capacity (J kg^{-1} K^{-1}) of the storage medium. If the specific-heat is constant, the amount of energy stored in the system is directly proportional to the rise in temperature of the storage medium.

$$C = c \int_{T_2}^{T_1} \Delta T \, dT \tag{5.2}$$

where c=m C_p.
Heat flow into and out of a store necessitates a temperature gradient, and heat transfer produces degradation of the energy. This degradation is further enhanced by the temperature change that takes place when the element is heated and cooled. From a practical point of view, this change in temperature over time will be a disadvantage. The charging and discharging of the TES system can be expected to be fully repeatable for an unlimited number of cycles. Some of the more common media used for sensible-heat storage are documented in Table 5.1. Water has one of the highest specific heat-capacity of all common materials, namely 4.18kJ/kg K which, together with its abundance, safety in use and relatively low economic cost, makes it a very suitable medium for sensible-heat storage. The difficulties of the high vapour-pressure of water and the limitations of other liquids, above 370K, can be avoided by storing thermal-energy as sensible-heat in solids.

Material	Specific Heat (J kg K^{-1})	Volumetric Capacity (10^6 J m^{-3} K^{-1})	Maximum Temperature (°C)	Thermal Diffusivity (m^2s^{-1})
Water	4180	4.18	100	liquid
Mineral oil	2717	2.36	250	liquid
Diphenyl/Diphenyl Oxide	2400	1.92	400	liquid
Sodium	960	0.91	880	liquid
Aluminium	896	2.63	660	8.4×10^{-2}
Iron	501	3.93	1000+	1.7×10^{-2}
Magnetite	752	3.85	1000+	5.0×10^{-7}
Concrete	1128	2.53	1000+	7.5×10^{-4}
Stone	878	2.41	1000+	7.5×10^{-7}
Brick	830	1.87	1000+	3.0×10^{-4}

Table 5.1: Sensible-heat capacity of selected materials

5.1.2 Latent-Heat Storage

Latent-heat energy is the energy absorbed during a phase transition from solid to liquid, liquid to gas (or vice versa) at, or close to constant temperatures. Phase-change materials (PCM) offer much larger heat-capacities over a limited temperature range than sensible-heat systems. Therefore, PCM storage density is higher than that for sensible-heat systems as use of the latent energy released in the transition from one phase to another is utilised. When heat is added to or removed from materials, phase-change can occur in a variety of ways such as melting; evaporating; lattice change; or changes in the crystal-bond water content [83]. TES systems which incorporate PCMs can offer increased energy-densities, because the latent heats of most materials are relatively large over a temperature variation of 20 K [84]. This may be a significant factor if space is a major consideration.

There are many PCMs available - see Table 5.2 - which fall into three broad categories (i) salt-hydrates; (ii) paraffins and (iii) non-paraffin organics. The main disadvantage to using PCMs is their relatively high economic cost, which for salt solutions can amount to up to £10/kg [85]. Salt hydrate (i.e. Glauder salt, Na_2SO_4 + $10H_2O$) decomposes at about 32°C to a saturated water solution of Na_2SO_4 plus a hydros residue of Na_2SO_4 and the resultant exchange of heat is 70 Wh/kg. The heat-storage capacity over a small temperature range is much larger than the capacity of water. Because civil-engineering costs are the major expense for a TES system, salt hydrates may become more economic than water storage under specific conditions [86].

Material	Melting Point (°C)	Heat of Fusion 10^5 J kg^{-1}	Volumetric Heat of Fusion. (10^8 J m^{-3})	Approximate Temperature change in mass equivalent water, (°C)
Water	0	3.34	3.34	80
Calcuim Chloride Decahydrate	29-36	1.74	2.84	42
Sodium Carbonate Decahydrate	32-36	2.67	3.85	64
Calcium Nitrate Tetraahydrate	41	2.09	3.82	50
Hypophosphoric Acid	55	2.14	3.22	51
Sodium	98	1.15	1.09	28
Lithium	180	6.28	3.32	150

Table 5.2: Latent-heat capacity of selected materials

5.1.3 Classification of the Thermal-Energy Storage Systems

It is important to identify some storage parameters, specified values of which could be used as design criteria.

- Energy-density (J/m^3) and specific-energy (J/kg).
- Storage-quality (temperature).
- Storage-efficiency (energy out/in ratio) and energy (or temperature) degradation.
- Energy-transfer rate (i.e. power) or storage and retrieval rate.
- Capital and operating costs and the energy involved in the fabrication of the storage system.

A classification of energy systems tends to be rather complex. In most cases two features of the system are crucial; the amount of energy to be stored and the duration of time that the energy must be held in store before it is transfered and utilised. Thermal-energy storage systems are commonly classified by temperature as either low temperature (operating below 420 K); medium temperature or high temperature. The different parameters listed above used to classify the TES system will be described.

Energy-density: The ratio of total energy to the volume or mass of the storage medium under investigation. Energy storage systems which involve the use of water as the storage medium will require significantly more volume per unit of energy stored than for bricks. When space is limited for the installation of any proposed storage system, then particular attention is paid to the energy-density of the medium employed.

Quality of storage: Quality, or grade, is the entropy, which is a measure of the disorderliness of the energy form. For thermal-energy the quality may be regarded as a function of the absolute temperature - a parcel of energy at 1000 K is more valuable than a similar parcel at 500 K. However, energy will never be utilised down to the absolute zero of temperature, but rather a finite temperature depending on the particular application. Energy is only useful if it is available at or above the temperature of application. In the above example, if the energy was required at 500°K then the first parcel would be worth twice as much as the second. This displays exchange-ability between quality and quantity, and the rate of exchange depends upon the final application of the energy.

Storage Efficiency: The storage of heat in water is limited by its ability to store heat effectively. An effective method of storage is achieved using the well insulated stratified store [87]. However, as a direct result of the charging process, the store can often be 'fully mixed' (i.e. the store is not well stratified), which reduces its effectiveness. Many other factors such as the effectiveness of the insulation, liquid or vapour contaminants, corrosion of the storage medium, structural design and cycling characteristics are also important for the overall acceptability of the systems [88].

Energy-transfer-rate: Once the energy has been retrieved successfully and stored, the primary concern will be the ease with which the stored energy can be utilised. This issue may be concerned with the heat-exchanger type or the distance between the store and the point of use, however, if a rapid transfer-rate is required then it may be necessary to reconsider the choice of storage medium selected.

Capital and operating costs: These - together with the value of the stored energy - will determine the rate at which the investment is paid off. As capital investment decisions are usually considered in relation to the pay-back period, the capital and operating costs will be significant for the investment appraisal. The capital costs for a TES-water system must also include those for additional pipes and fitting costs as well as the storage unit itself.

Storage-scale: The scale of which storage is required is important because it considerably influences the optimal type of plant selected and the manner of operation. Storage methods that merit consideration on one scale may be quite inappropriate on another. An illustration is pumped-water energy storage, which is economical only on a large scale where natural reservoirs are available at different altitudes.

5.1.4 Applications of Thermal-Energy Storage

Energy storage is especially important where the energy supply is intermittent, such as with solar energy. The use of intermittent energy sources is likely to grow [82]. The benefits of thermal-energy storage can be applied wherever energy is produced or consumed - see Figure 5.2. TES systems have been installed successfully at industrial, commercial and domestic premises for many years.

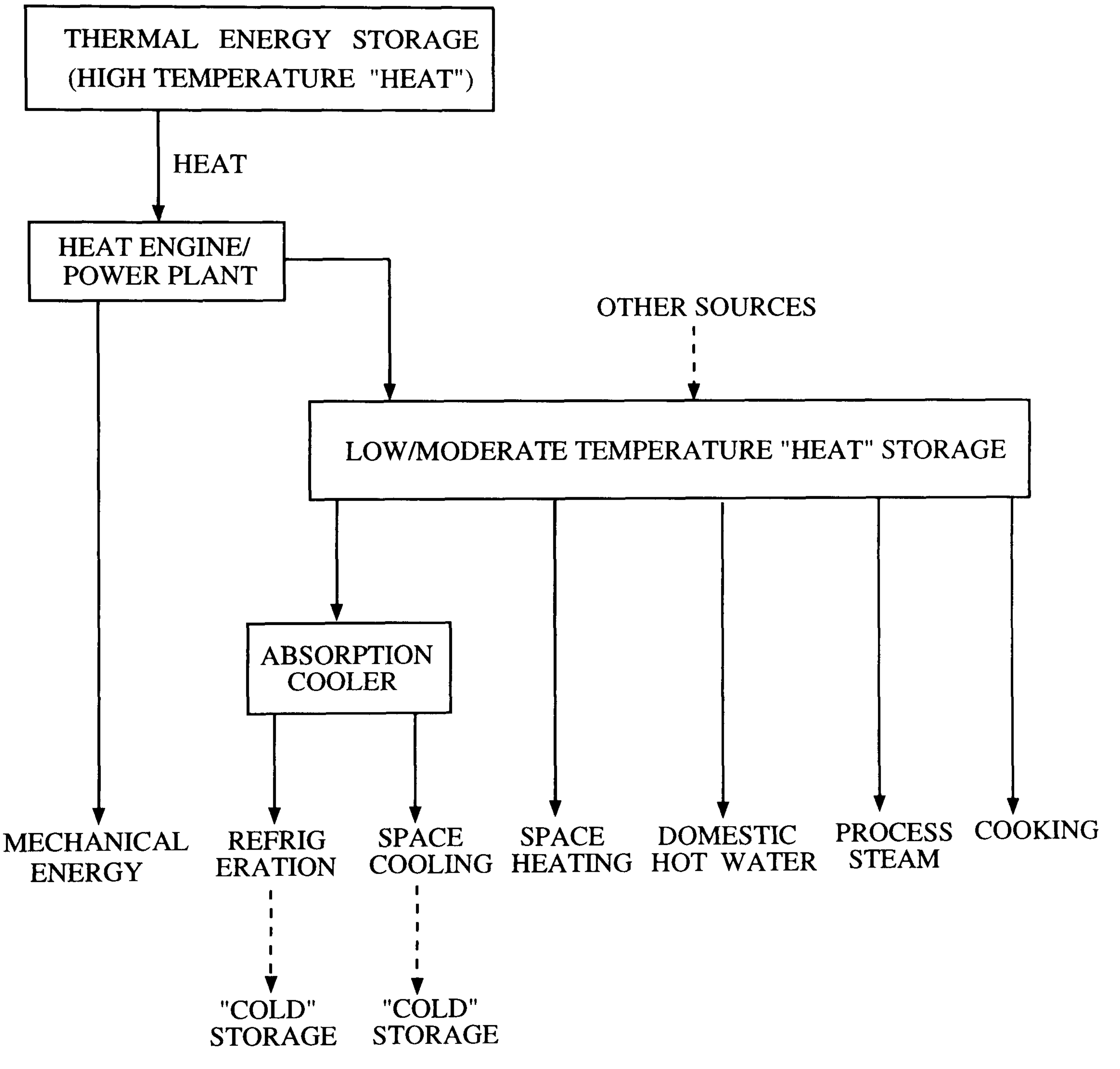


Figure 5.2: Energy storage options.

5.2 The Application of Thermal-Energy Storage to Small-Scale Combined Heat-and-Power Systems

An issue which appears to limit the usefulness and applications for CHP is the daily mismatch between the demand for electricity and the thermal-energy load requirement for an industrial facility or building. Figure 5.3 highlights the question of how much of the heat produced by the CHP unit is actually utilised on-site. One of the main objectives to achieve for the successful application of CHP is to ensure that the maximum quantity of heat is used. The storage of heat can, under appropriate circumstances, bridge the gap between the supply and demand for energy where CHP systems have been installed.

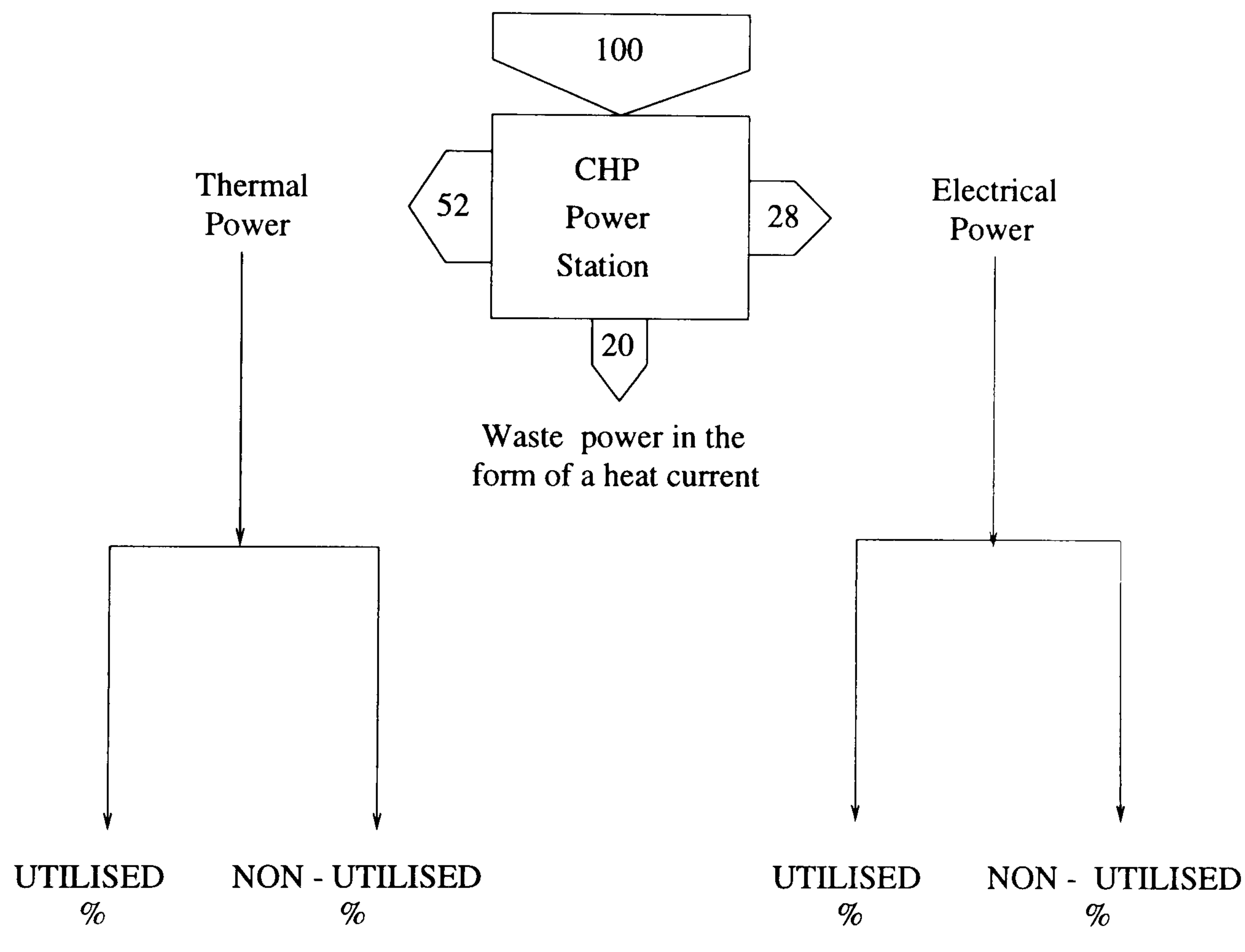


Figure 5.3: Utilisation of heat and power for sites.

The demand for heat has a marked peak in the early hours of the morning for many cases and is illustrated in the case of the hotel - see Figuremismatch. The supply of heat from the 70 kW_e CHP unit is partially out of phase with demand from the hotel. TES systems can be considered as buffers which can compensate for this mismatch between the supply and demand of thermal-energy. Effective utilisation can lead to an increase in the average-to-maximum power rating. Therefore. thermal-energy storage has a significant role to play in energy conservation.

TES can complement CHP in the following ways:

- Utilising more of the waste-heat created through the production of electricity: and optimising what are already highly-efficient systems
- allowing the installation of smaller CHP units to satisfy the base heat load.
- Enabling CHP to be installed in other applications. which would ordinarily fall outside the tight economic criteria set for CHP installation.

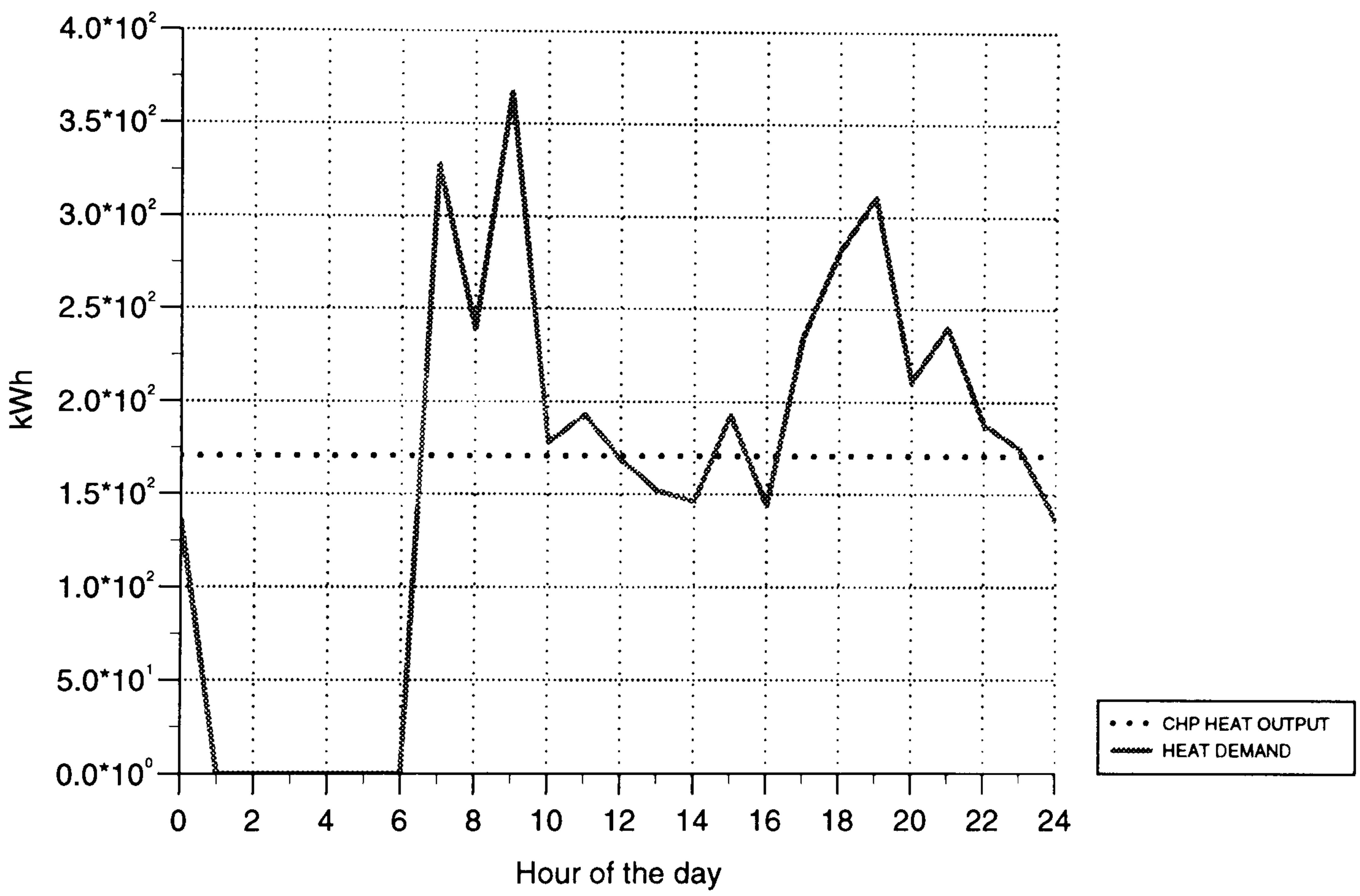


Figure 5.4: Graph showing the daily mismatch between CHP, output and demand

Large-scale CHP systems have utilised energy-storage successfully for many years. for cooling and heating. As proven technologies individually, increasing integration has led to decreasing capital investment costs and increasing annual energy cost-savings [46]. Large-scale systems have also utilised TES to store cold (through the use of absorption chillers) to produce ice at off-peak periods. Chilled water is then produced from the ice at peak times, usually during the day [89]. The use of heat accumulators in district heating networks can store heat which will be used later for power generation [90]. There are numerous other examples of the successful application of the integration of CHP and TES on a large-scale. However.

the case for the integration of these two technologies on a small-scale is yet to be proven.

CHP sizing methodology and thermal-energy storage.

Small-scale CHP units are usually sized to supply the base thermal-load. This will lead (in most cases) - where there exists a suitable demand for the electricity produced - to the shortest possible economic pay-back period for the installation. Under these circumstances, it is unlikely that any excess heat will be produced by the CHP unit where there exists a constant heat-load. Consequently, the need for energy-storage will not arise. If heat-demand is not constant, the potential for utilisation of TES will depend on the operation of the CHP unit. When operation is modulated on thermal-demand (turndown maximum is usually to 50%) there will be no excess heat available for storage. However, if the CHP unit is sized on base electrical-load, the potential for the application of TES looks more promising. An alternative sizing strategy might be to deliberately oversize the CHP unit so that energy is available for either export or storage. This would be a highly controversial strategy and would not produce the shortest pay-back period for the investment.

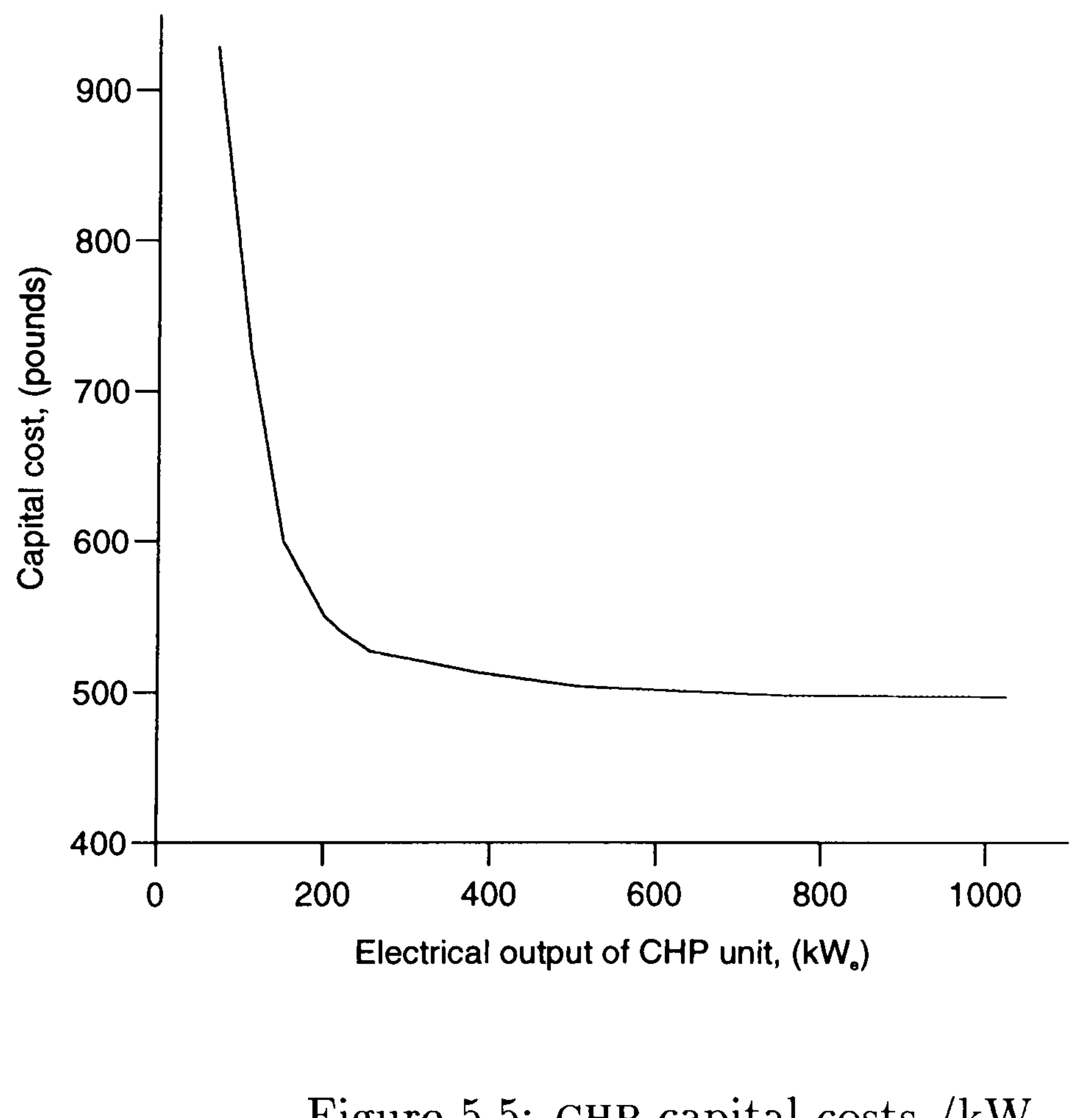


Figure 5.5: CHP capital costs /kW$_e$.

There are, however, powerful factors working to the advantage of larger plants where small-scale CHP is concerned. These factors concern the capital and operating costs of CHP installations. Figure 5.5 shows a significant reduction in capital cost per kW of electricity generating-capacity that occurs as the size of the CHP unit increases, in the range 20kW$_e$ to 200kW$_e$. This means that an installation equipped with a 100 kW_e generating set may cost only 50% more than an equivalent installation using a 50 kW_e set [91].

In terms of operating costs, there are two factors which provide larger installations with an advantage. Firstly, power generating efficiency improves as plant size increases. For example the electrical generating efficiency for a typical 50 kW_e engine might be 29%, whereas the efficiency for a 100 kW_e engine could be 2% higher at 31%. As fuel costs over the lifetime of an installation in this size range are likely to amount to over five times the capital costs, a relatively small improvement in generating efficiency will have a major improvement on the overall economics of the CHP scheme. Secondly, maintenance costs will tend to fall as the engine size increases. Once again, comparing 50 kW_e and 100 kW_e CHP sets, typical maintenance costs are likely to be approximately 1.3 and 1.2p/kWh of electricity generated, respectively. As maintenance costs for a small-scale CHP system typically equate to 35% of gross energy savings, a small reduction in unit costs will make a substantial difference to life-cycle economics [91].

5.2.1 Selection of Storage Media for the Application to Small-Scale CHP Systems.

One criteria governing the selection of a storage material that is clearly important is specific heat per unit volume at the operating temperature. If volumetric considerations have to be taken into account, then the product of specific heat and density are the significant parameters. In the case of small-scale CHP installations it is unlikely that storage space will be significant over cost. Consideration of cost (low) and specific heat-capacity (relatively high) from Table 5.1 suggests the selection of water as the most suitable medium for thermal-energy storage in CHP systems for applications below 100°C. This decision is further supported because the main cooling and heat distribution liquid in CHP systems is commonly water. Therefore, water could be used directly where possible as a storage medium thus reducing conversion losses

Thermal-energy storage in water has the following advantages:

1. Water is easy to handle, non-toxic and non-combustible.
2. It has a high density and specific-heat.
3. Possesses excellent transportation properties (good thermal conductivity and low viscosity).
4. Can be used as both a storage medium and a working fluid.
5. Interfacing the TES with HVAC equipment is relatively easy.
6. Charging and discharging of energy can occur simultaneously.
7. With proper specification, almost uniform discharge temperature is possible.

8. Water tanks may be located above ground or underground.

9. Simple control techniques can be used.

10. Flow can be arranged to take place by thermosiphon action.

11. Operating cost is very reasonable.

Disadvantages of thermal-energy storage in water

- Water will freeze below 0^oC or boil above 100^oC thereby limiting the useful temperature range.
- It is a corrosive medium.
- Has a low surface tension - and so can leak easily through pinholes or other ruptures.

Sizing the TES unit
The volume V of the TES tank will depend on the method of heat-storage chosen (eg. sensible or latent-heat storage) and the properties of the materials used. Water has a relatively high specific-heat capacity (C_p) per unit cost, is safe to handle and easy/safe to dispose of into the environment. Not all storage media will have the same advantages and whilst some will have a significantly higher values of C_p, their costs of disposal or other factors might be unacceptable.

5.2.2 Energy Output from CHP Units

Heat and electricity is produced simultaneously by CHP units. The operating temperatures of each section of a typical gas-fired reciprocating 70 kW_e, 114 kW_T CHP unit are given in Figure 5.6.

The total energy in the system will comprise of the four separate components as described in equation (5.3).

$$\dot{Q} = \dot{E}_{out} = \dot{E}_{electricity} + \dot{E}_{condenser} + \dot{E}_{stack} + \dot{E}_{radiated} \tag{5.3}$$

The heat-output from the CHP unit will be determined by a combination of the 'temperature-lift' (ΔT = T_f - T_r) through the engine, and the mass-flow rate. $\dot{m}$ of the water through the engine. For the CHP unit in Figure 5.6 operating at steady state conditions with $\dot{m}$ equal to 150 litres/minute (2.5 l/s), the rate of heat-output is:

$$\dot{Q} = \dot{m} \;\; C_p \;\; \Delta T \tag{5.4}$$

$$= 2.5 \times 4180 \times 11 = 114.9kW \tag{5.5}$$

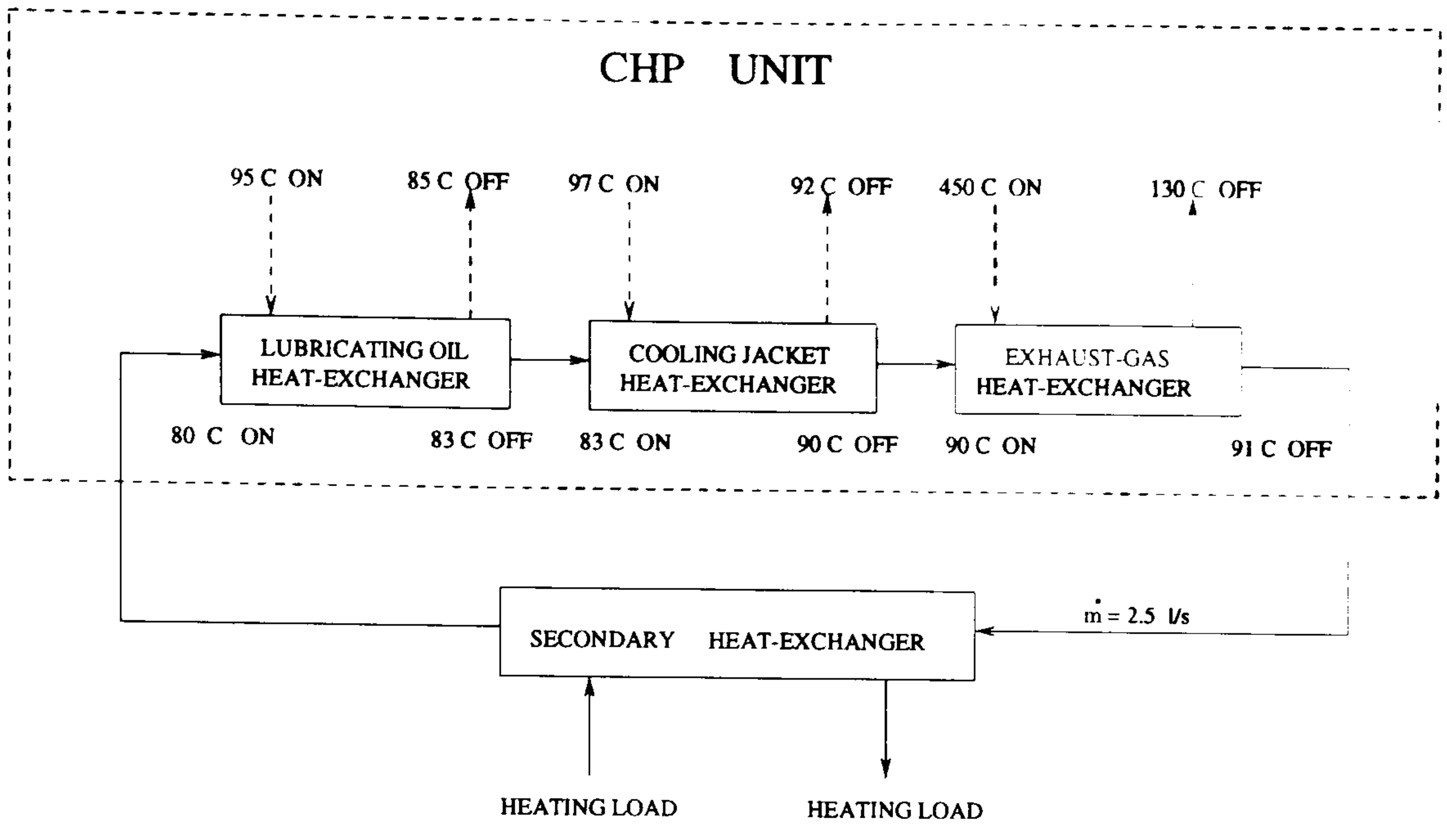


Figure 5.6: Approximate heat input/output temperatures for a gas-fired 70 kW_e reciprocating CHP unit.

For varying flow and return temperatures the total energy supplied can be determined from:

$$Q = \int_0^t V C_p \rho (T_f - T_r) dt \tag{5.6}$$

for a constant 'ΔT' (i.e. at steady state conditions), density & specific heat this reduces to:

$$Q = k \int_0^t V dt \tag{5.7}$$

where

Q	energy supplied (kJ)	k	V C_p ρ ΔT
$\dot{Q}$	power (kW)	T_f	f(t)
V	volume flow(m^3/s)	T_r	f(t)
T_f	flow temperature (^oC)	t	time
T_r	return temperature (^oC)		
C_p	specific heat (kJ/kg^oC)		
ρ	density (kg/m^3)		

The operational plan for the integrated CHP/sc tes system is that the heat recovered from the lubricating oil, jacket's cooling-water and the exhaust-gas will be stored in a heat-storage tank as sensible-heat in water.

If applied successfully to CHP systems, heat-storage units could produce the following benefits which ultimately might result in the increased uptake of CHP technology.

Potential benefits of an integrated TES/CHP system

- The maximum heat-output from the CHP unit can be reduced because the heat-energy stored can be employed to cut demand-peaks.
- Operating costs can be reduced through the more efficient operation of the CHP equipment at maximum loading, i.e. when thermal-efficiencies are at their highest. The energy can also be generated at periods with lower fuel prices if available.

Drawbacks of an integrated TES/CHP system

- The relatively high capital cost of the TES unit together with installation and associated running costs.
- Heat losses associated with the conversion, transport and storage of thermal energy.

Ultimately the result is a trade-off between the desired benefits and the drawbacks.

5.3 Predicting the Energy Available for Storage in the Integrated CHP/TES System.

It has been demonstrated (see Chapter 1) that there are significant benefits resulting from the integration of large-scale CHP and TES. When utilising CHP and energy storage the main objective is to use the energy produced where and when required, and then only store the surplus. As CHP units produce heat and electricity simultaneously, it is necessary to consider the effects of electricity supply and demand in the system even though the emphasis is being placed on the storage of thermal energy. Note that the case of electricity storage will not be considered in detail in this research as it is possible to export excess electricity directly to the grid. In order to predict the potential benefits of an integrated CHP/TES system, a mathematical model has been developed and applied to the five test case-studies; namely a hotel, a hospital, a leisure complex, a block of flats and a slaughter house - see Chapter 4 and Figures 5.10 to 5.15 for a detailed description of each site's energy-demand profile and configuration.

For heat and electricity storage, three operational patterns were considered for each of the five case studies:

(**Operational Pattern 1**) 17 hours per day running without modulation.

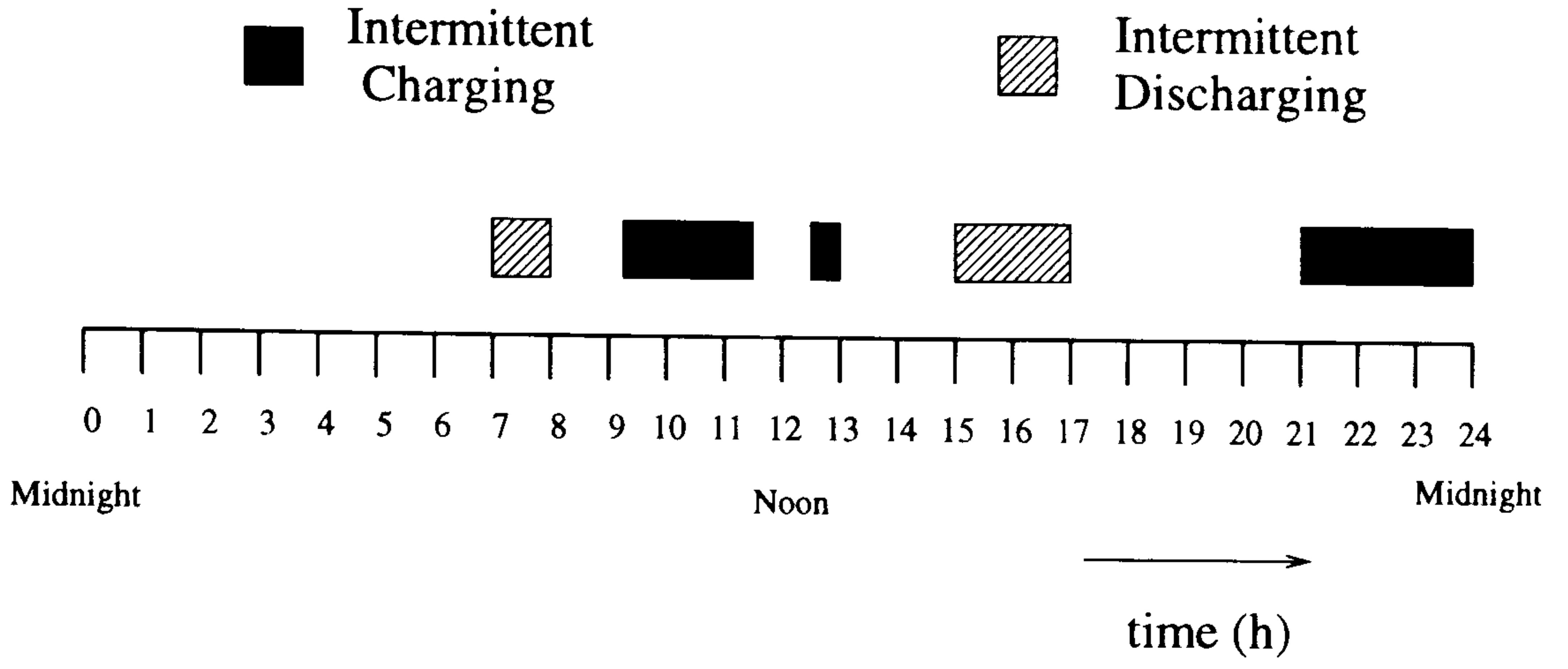


Figure 5.7: Time intervals for peak-charging of, and discharging the storage system by the CHP unit on a normal day.

(**Operational Pattern 2**) 24 hours per day CHP operation, storing the off-peak generated heat only for reuse at peak times.

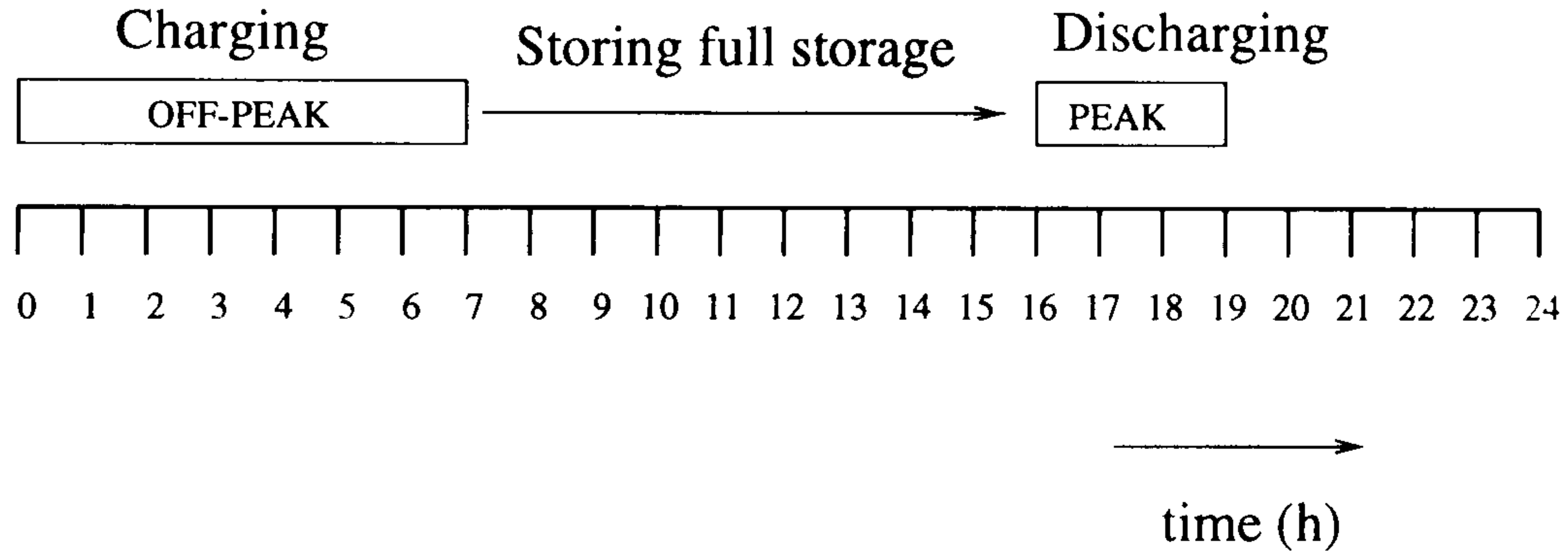


Figure 5.8: Time intervals for peak and off-peak charging and discharging the storage system from the CHP hot-water on a normal day.

(**Operational Pattern 3**) Items 1 and 2 combined.

CHP units of sizes 70kW$_e$, 507kW$_e$, 200kW$_e$, 48kW$_e$ and 255kW$_e$ have been selected for the hotel, hospital, leisure complex, flats and industrial building respectively. The model examines the profiles for heat and electricity demands from the case studies and predicts the maximum potential energy, environmental and economic savings, that can be obtained through the storage and subsequent use of excess heat produced by the CHP unit for a variety of operational patterns. For details of the operating specifications of the small-scale CHP units utilised in this study, refer to Chapter 4.

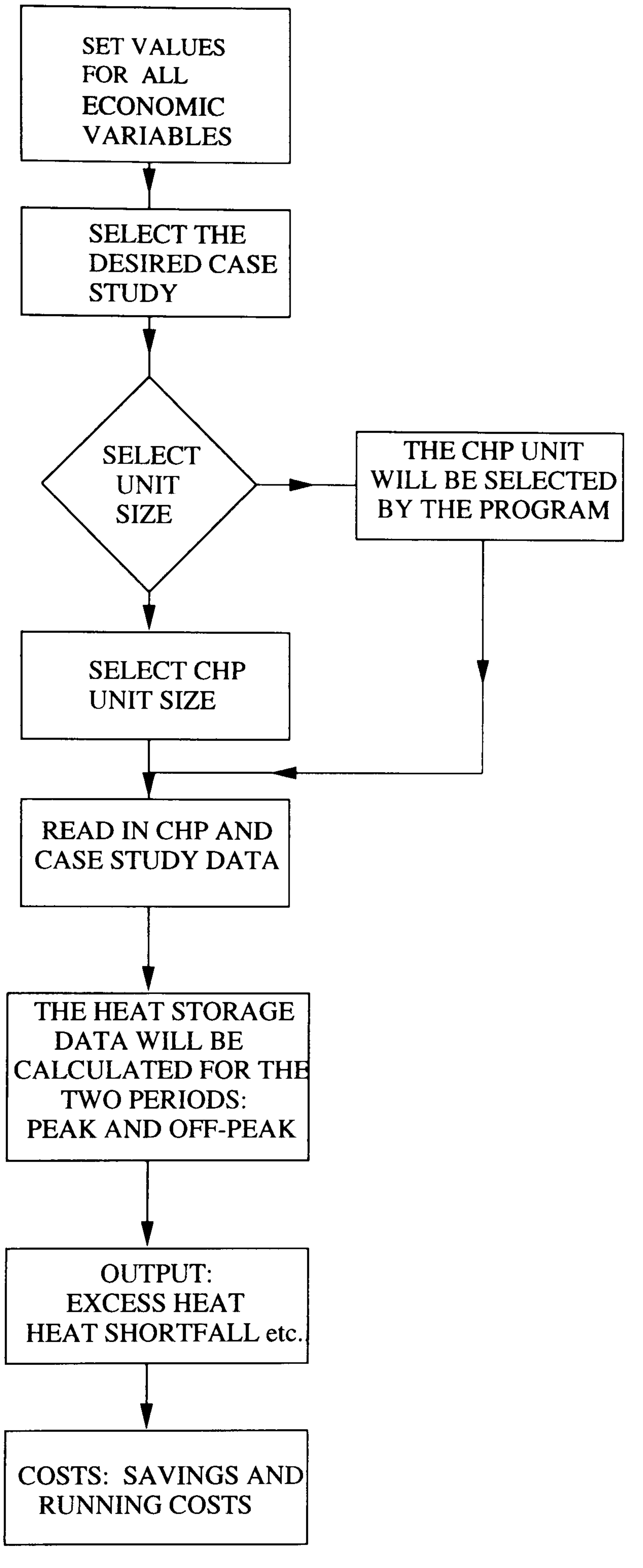


Figure 5.9: Thermal-energy storage data model flowchart.

5.3.1 Heat-Storage.

A computer model was developed in Fortran 77 in order to predict the potential for heat-storage for the three test cases - see Figure 5.9 for an outline of the programs structure. Tables C.1 to C.5, which are given in Appendix C summarise the results produced by the predictive model when applied to the five case studies. Certain assumptions have been made regarding the availability of the CHP unit and the heat losses from the TES system. It was assumed that the units would be available for 100% of the required operational hours, usually 365 days/year. Additionally, the heat losses from the TES unit are assumed to be negligible. This will not be the case in reality. However, it is important to first determine the outline potential for the integrated systems before time, money and effort are spent on a more detailed examination.

Explanation of the heat-output Tables C.1-C.5:
The output given in the tables is broadly split into two sections, peak and off-peak, which correspond to 17 hours/day and 24 hours/day operation of the CHP unit respectively. Columns 1-9 in the tables are explained below:

1. Month: The month of the year for which the data refer.

2. Heat from CHP unit (off-peak): Gives the total heat produced by the CHP unit in kWh during the off-peak hours, which are currently set at 12.00am to 07.00 am for each day in the given month.

3. Heat demanded by site (off-peak): The total heat demanded from each case study in kWh for each day for the seven hour off-peak period.

4. Heat available for store (off-peak): The total heat that could potentially be utilised in a TES system in kWh calculated for each day after the off-peak heat demand has been supplied by the CHP unit.

5. Value of heat store (off-peak): The value in £sterling at current unit prices for the above quantity of heat energy - energy rates are currently set at 25p/therm for gas, 5.5p/kWh (peak) and 1.7p/kWh (off-peak) for electricity and a boiler efficiency of 75%.

6. Heat available for store (peak): The heat potentially available for storage which has been produced by the CHP unit during peak times calculated in kWh after the peak demand for heat has been supplied.

7. Heat short fall per day (peak): The quantity of heat still required in kWh over and above that produced by the CHP unit.

8. Max heat stored per day (peak): The maximum possible quantity of heat energy available for storage each day in kWh. This figure is governed by the available heat energy and the demand from each site.

9. Value of heat saved (peak): The value in £sterling of the above heat energy at current unit prices - currently set at 25p/therm for gas, 5.5p/kWh (peak) and 1.7p/kWh (off-peak) for electricity and a boiler (unspecified type) efficiency of 75%.

10. CO_2 Savings: The potential quantity of carbon dioxide in kg which will not be emitted as a direct result of the application of the integrated system.

Heat-storage observations from Tables C.1-C.5 - see Appendix C:
Each of the five case-studies was examined to determine the benefits and value of the integrated system. All of the cases shown have failed to produce greater savings from the heat stored together with the heat and electricity displaced at off-peak times, than the running costs for the CHP unit. When the CHP units are operated for the seven off-peak hours, the off-peak demand for heat and electricity will be satisfied before energy is offered for storage. This will result in a reduced net running cost for the CHP units during off-peak periods. Note that the unit price for electricity will be calculated at the off-peak rate of 1.7p/kWh.
It appears from Tables C.1 - C.5 that, if the heat demand from the case studies was more intermittent or peaky, then the case for TES might be dramatically improved. The costs of running the CHP units at off-peak times for seven hours per day (at current given energy prices) are £5,449, £38,786, £14,527, £3,727 and £18,614 for hotel, hospital, leisure complex, flats and industrial building respectively.

The hotel:

There are two daily peaks for heat demand at the hotel, one at 6.00am and the other at 6.00pm - see Figure 5.10. For operational pattern 1, the maximum annual potential for heat-storage of 46.2 MWh was predicted, which is equivalent to an economic value of £526 at the given energy prices. This result was obtained when the site was supplied by a 220kW$_e$, 343 kW$_T$ CHP unit - see Table 5.3. Operational pattern 2 indicated heat savings of of up to 195.9 MWh, which is equivalent to £2,228 with a $70kW_e$, 114 kW$_T$ unit.

CHP UNIT SIZE kW$_e$	YEARLY HEAT-STORAGE SAVINGS FOR CHP OPERATION AT: PEAK PERIODS Economic £	Heat MWh	CO_2 tonnes	OFF-PEAK PERIODS Economic £	Heat MWh	CO_2 tonnes
32	1	0.12	0.31	1353	119	30.9
48	95	8.3	2.2	2031	179	46.2
70	157	13.8	3.6	2228	196	50.9
110	410	36.1	9.4	2139	188	48.8
150	485	42.6	11.1	1770	156	40.5
220	526	46.2	12.0			

Table 5.3: Predicted annual maximum savings produced as a result of the installation of the integrated system at the hotel for a selection of CHP unit sizes.

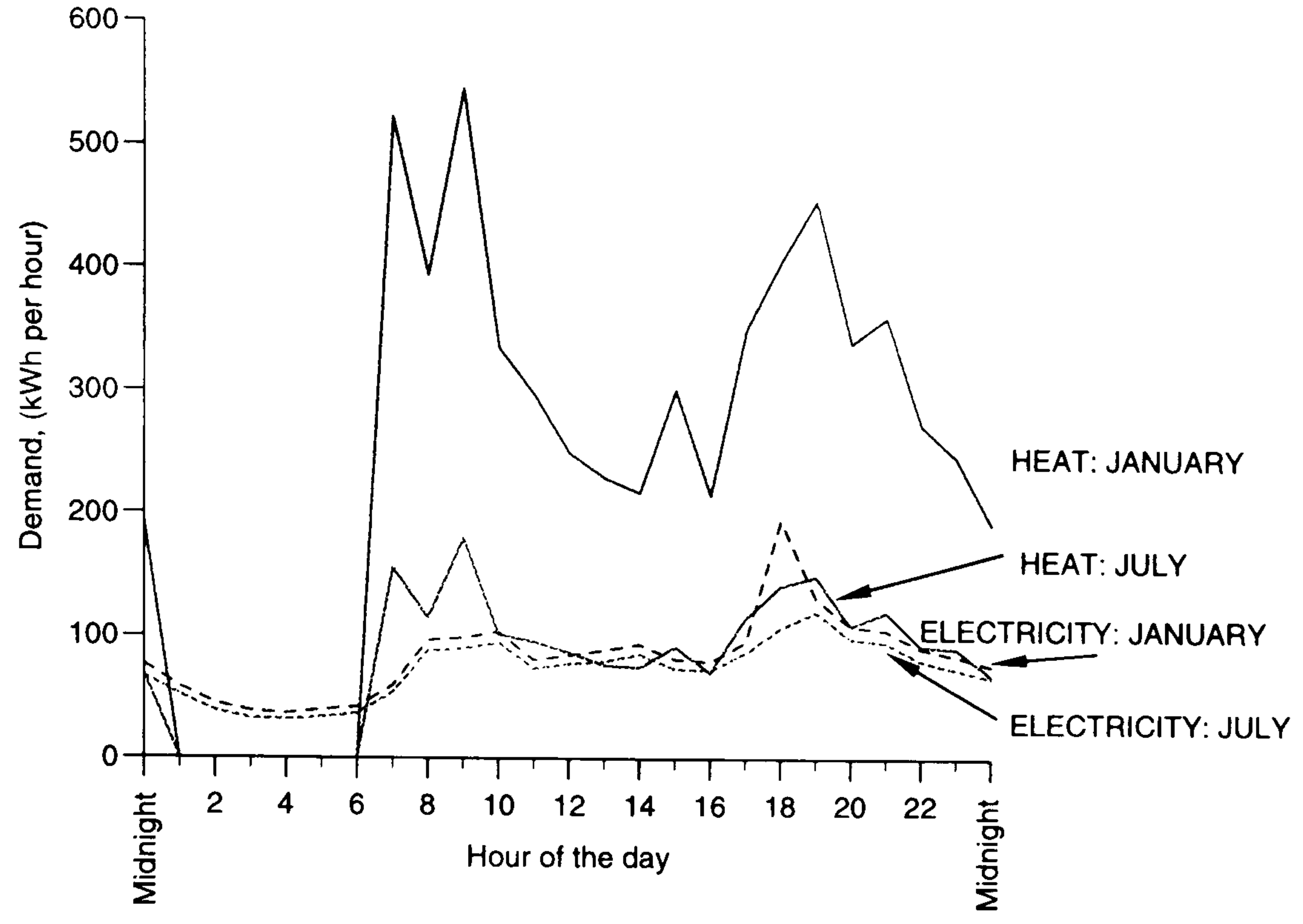


Figure 5.10: Hourly heat and electricity demand profile for the hotel.

Off-peak heat-storage

Figure 5.10 shows that the hotel has no off-peak demand for heat between the hours of midnight and 6.00am. If the CHP unit is operated at these times, the heat can be stored for use at peak times where economically practical. During the off-peak period, one hour of heat-output from the CHP unit is consumed at the time of production for each day of the year. The remaining six hours of off-peak heat production, which amounts to 684kWh/day, can be stored for use later in the day. Annually, this would amount to a total of 249.66 MWh of potential heat-storage. However, as a result of reduced thermal-demand in the summer period (i.e. June to September), the maximum useful off-peak storage potential for the hotel with a 70 kW_e CHP unit installed is 195.9 MWh. If this heat is stored and consumed without losses, the emission of approximately 50.9 tonnes of CO_2 could be eliminated.

There is a demand for electricity throughout the off-peak period. However, as electricity can be imported for about 1.7p/kWh (maintenance costs for this sized unit would be 0.86 p/kWh_e), it would not be considered economically viable to operate the CHP unit at these times. Figure 5.11 illustrates how, for a 70 kW_e unit, the unit gas price will need to be below 19p/therm in order for the system to be economically viable at off-peak times. The economic viability of operating the CHP unit at night and storing the heat produced will be totally dependent on the gas and electricity prices where the demand for energy exists. If heat losses are also considered, then the real unit gas price for break-even is likely to be in the region of 15p to 17p /therm. This gas price - while possible - is unlikely to form a sound basis for the economics of the integrated system. Unless the price of gas falls below 15p/therm there will be no contribution towards the capital and installation costs of the system. Collectively, these factors will mean that there is little/no potential for heat-storage using the heat produced at off-peak times.

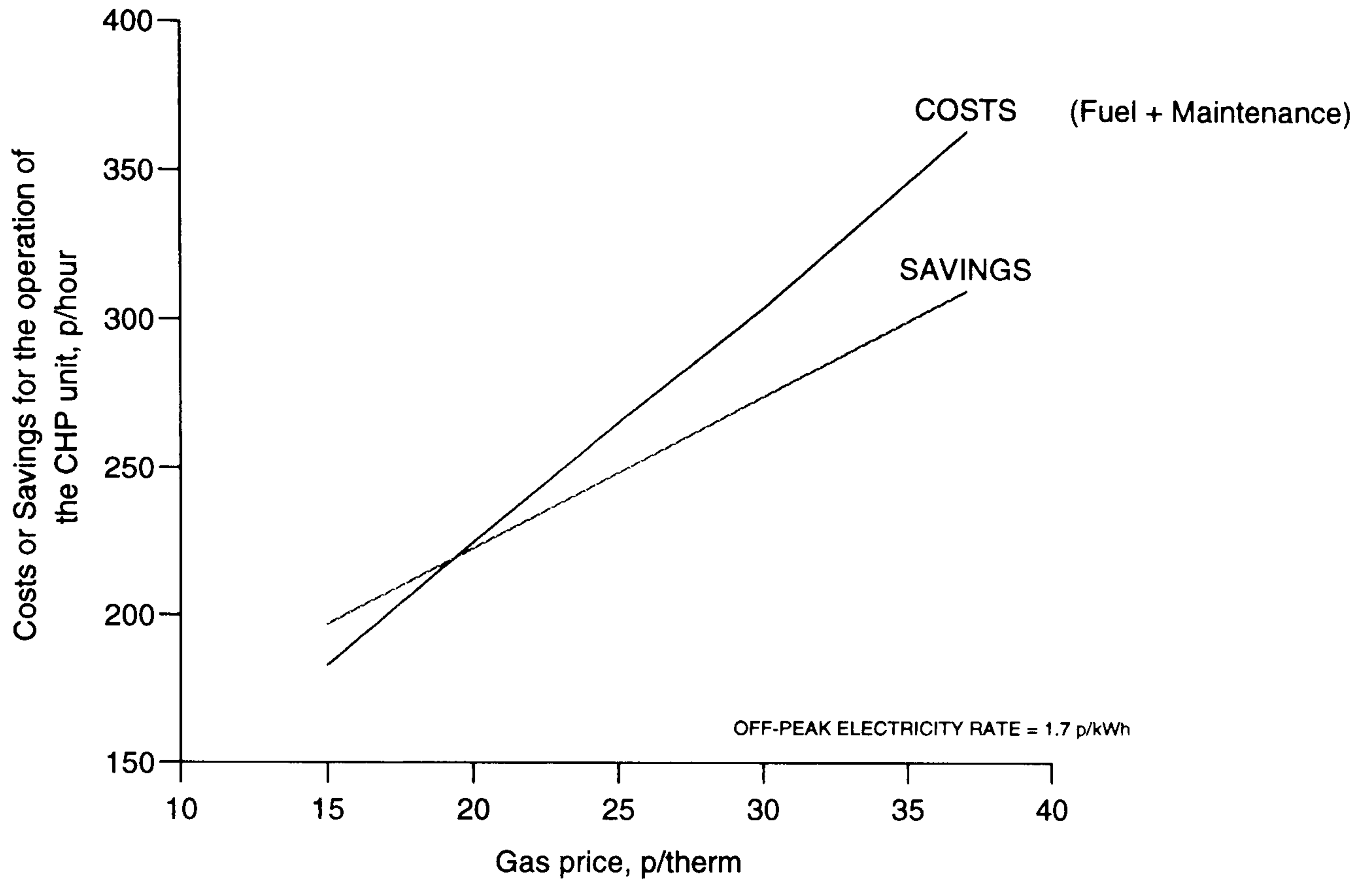


Figure 5.11: Costs-Savings analysis for the off-peak operation of a 70kW$_e$, 114 kW$_T$ CHP unit for varying gas prices.

Peak-time heat-storage potential.

The potential benefits resulting from storing the heat produced at peak times was also examined. It was determined that significant quantities of heat were only available for storage during the months June to September at the hotel. The potential heat for storage and use amounted to 13.8 MWh annually, which would displace almost 3.6 tonnes of CO_2 emissions annually (assuming no thermal-losses) providing that the electricity produced by the CHP unit can also be totally utilised.

The hospital:

The hospital has the greatest demand for heat of any of the case studies with an average heat-to-power demand ratio of 6:1 and a base heat-load of more than 1800kW for each month of the year - see Figure 5.12. Consequently, only the 1025kW$_e$, 1423 kW$_T$ CHP unit will produce any excess heat for storage. The total yearly heat available in this extreme case is still only approximately 11.8 MWh, which costs less than £135.
The installation of an integrated CHP/TES system at the hospital may be viable for larger CHP units. However, these would fall outside the scope of this thesis. The electricity demand at the hospital can be satisfied by a small-scale CHP plant (as defined in this research). However, the base heat-demand exceeds 1,800 kW, i.e. greater than the heat-output of the small-scale CHP units selected.

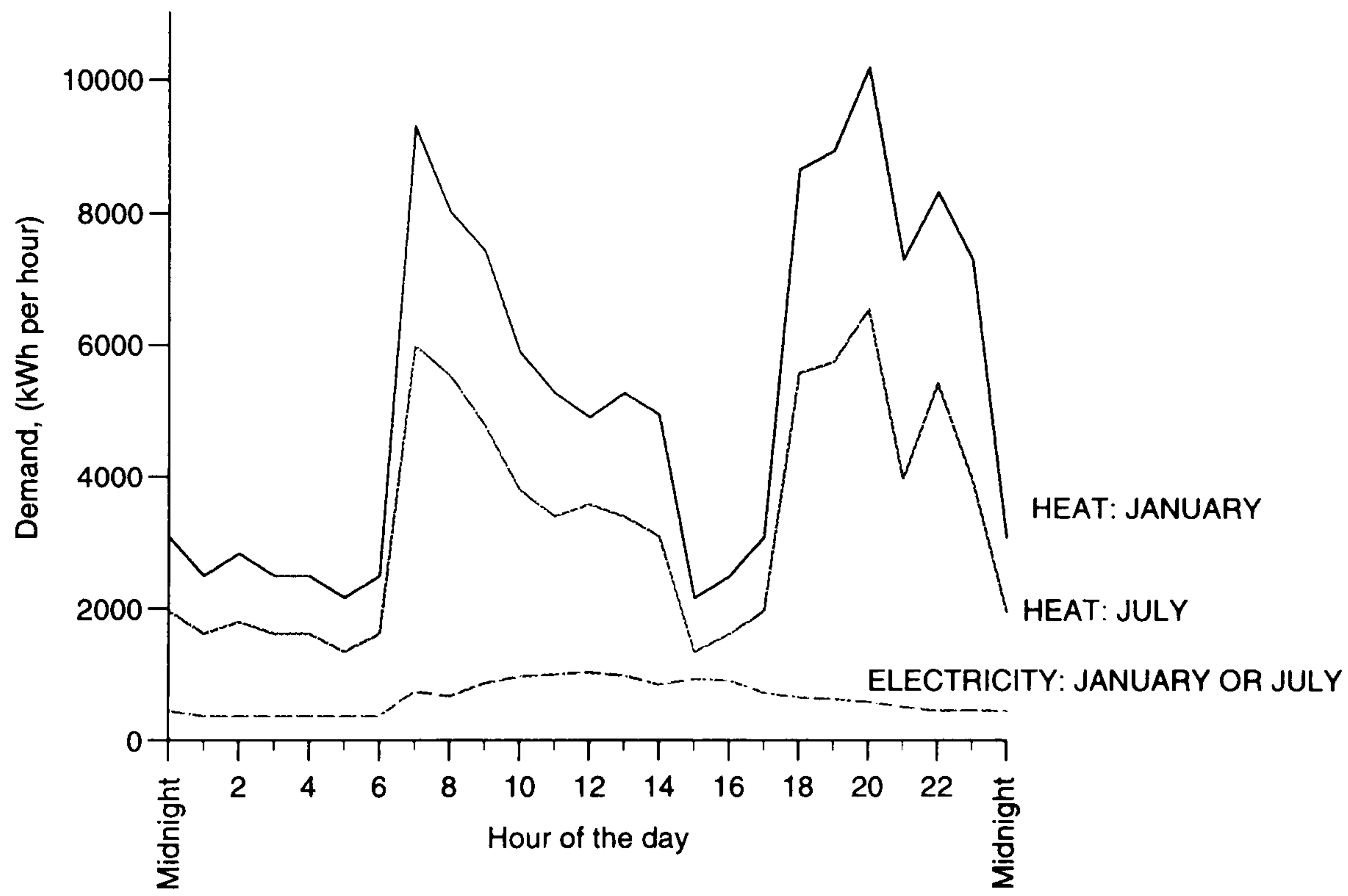


Figure 5.12: Hourly energy-demand profile for the hospital.

The leisure complex:

It was not possible to produce any surplus heat which could be utilised by the leisure complex on a day-to-day basis. This is because the daily heat-demand profiles have been predicted from a combination of the monthly energy-bills and the estimated daily heat-use pattern. Consequently, the daily heat-demand profile is very flat and there is no potential for heat-storage at the site. The leisure complex operates an indoor swimming pool, which has a large heat demand and in effect the pool will act as a heat-store for the system by absorbing heat at times of spare capacity from the CHP unit.

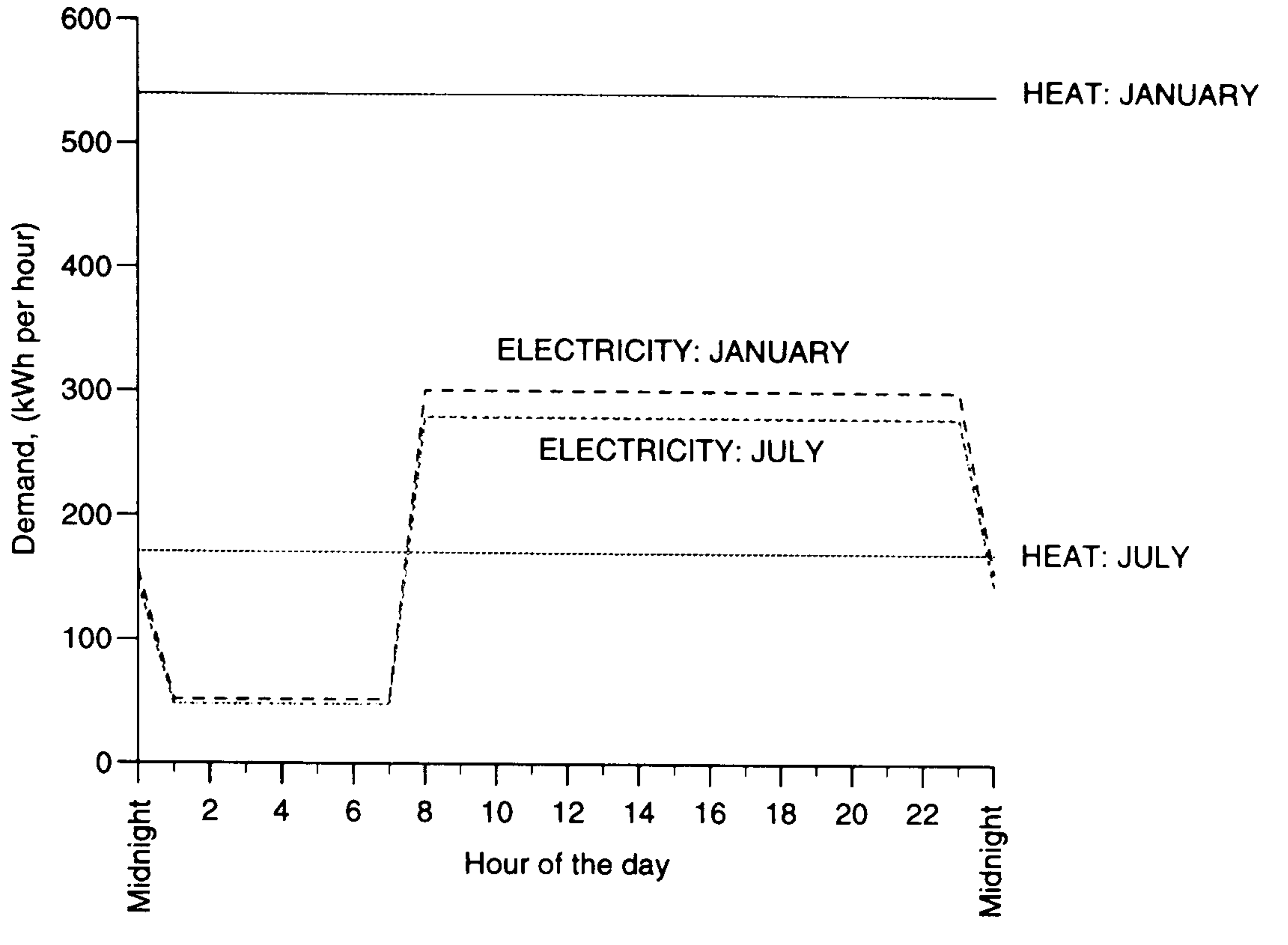


Figure 5.13: Hourly energy-demand profile for the leisure complex.

The block of flats:

The high heat-to-power ratio of the flats displayed in Figure 5.14, dictates that there will be very little thermal power available for storage from the smaller CHP units, i.e. less than 70kW$_e$. The demand for energy is relatively small with the electricity demand being easily satisfied by the smaller CHP units.

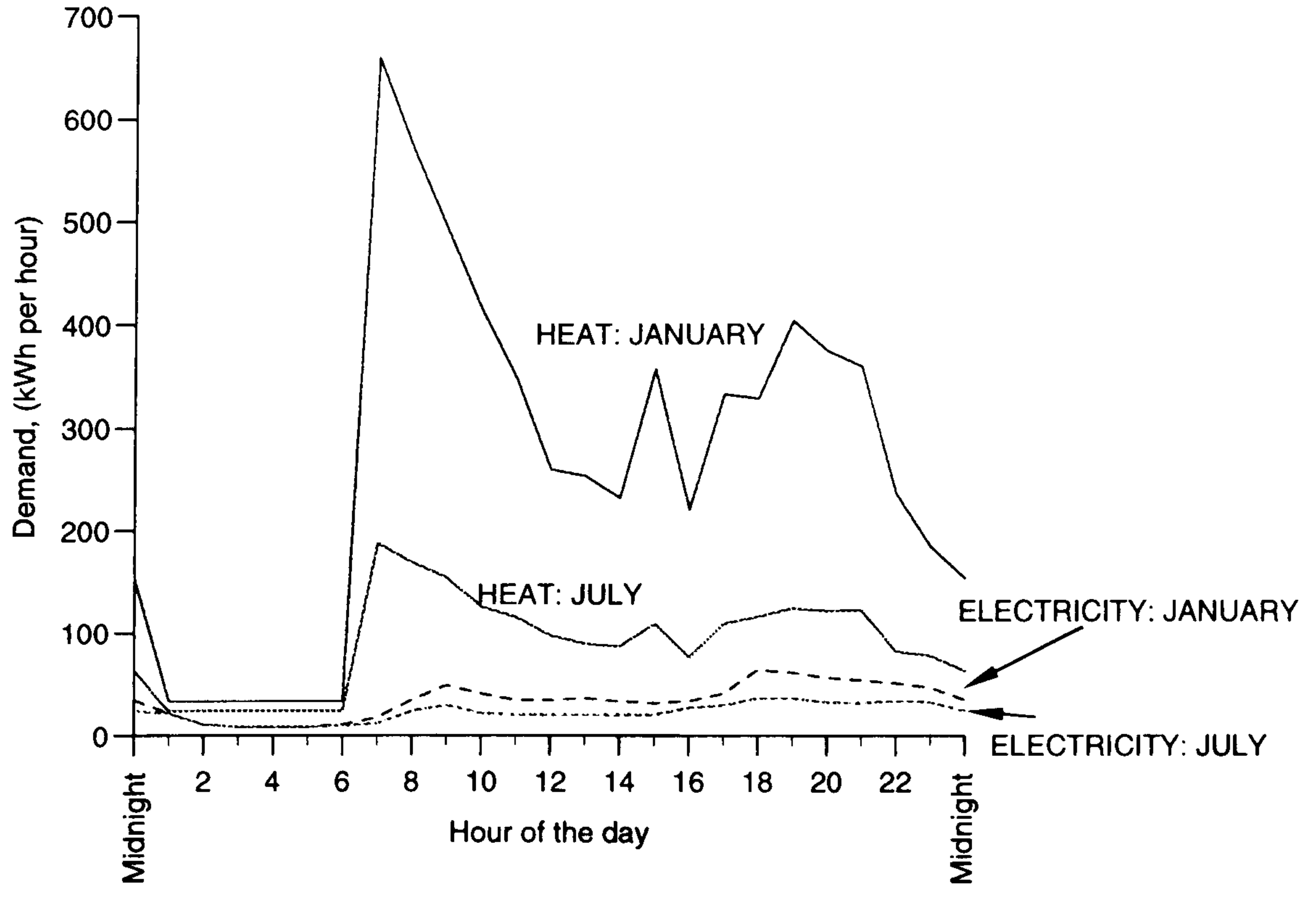


Figure 5.14: Hourly energy-demand profile for the residential block of flats.

The 48kW$_e$ CHP unit example shows an off-peak potential heat-storage capability of 132.3 MWh for the year, i.e. equivalent to £1.501 worth of off-peak fuel savings, which could result in the elimination of up to 34.3 tonnes of CO_2 emissions annually. Therefore, significant potential for heat storage at this site will only occur if the CHP unit is operated during the 7 off-peak hours each day. However, the same economic limitations - low off-peak electricity prices and relatively high gas prices - for off-peak heat-storage previously indicated will also negate any potential for economically-viable savings in this case.

CHP UNIT SIZE kW$_e$	YEARLY HEAT-STORAGE SAVINGS FOR CHP OPERATION AT: PEAK PERIODS			OFF-PEAK PERIODS		
	Economic £	Heat MWh	CO_2 tonnes	Economic £	Heat MWh	CO_2 tonnes
32	0	0	0	664	58	15.1
48	156	13.8	3.6	1501	132	34.3
70	329	28.9	7.5	1308	115	29.9
110	181	16.0	4.2	1262	111	28.8

Table 5.4: Predicted maximum annual savings produced as a result of the installation of the integrated system at the flats for a selection of CHP unit sizes

The slaughter house:

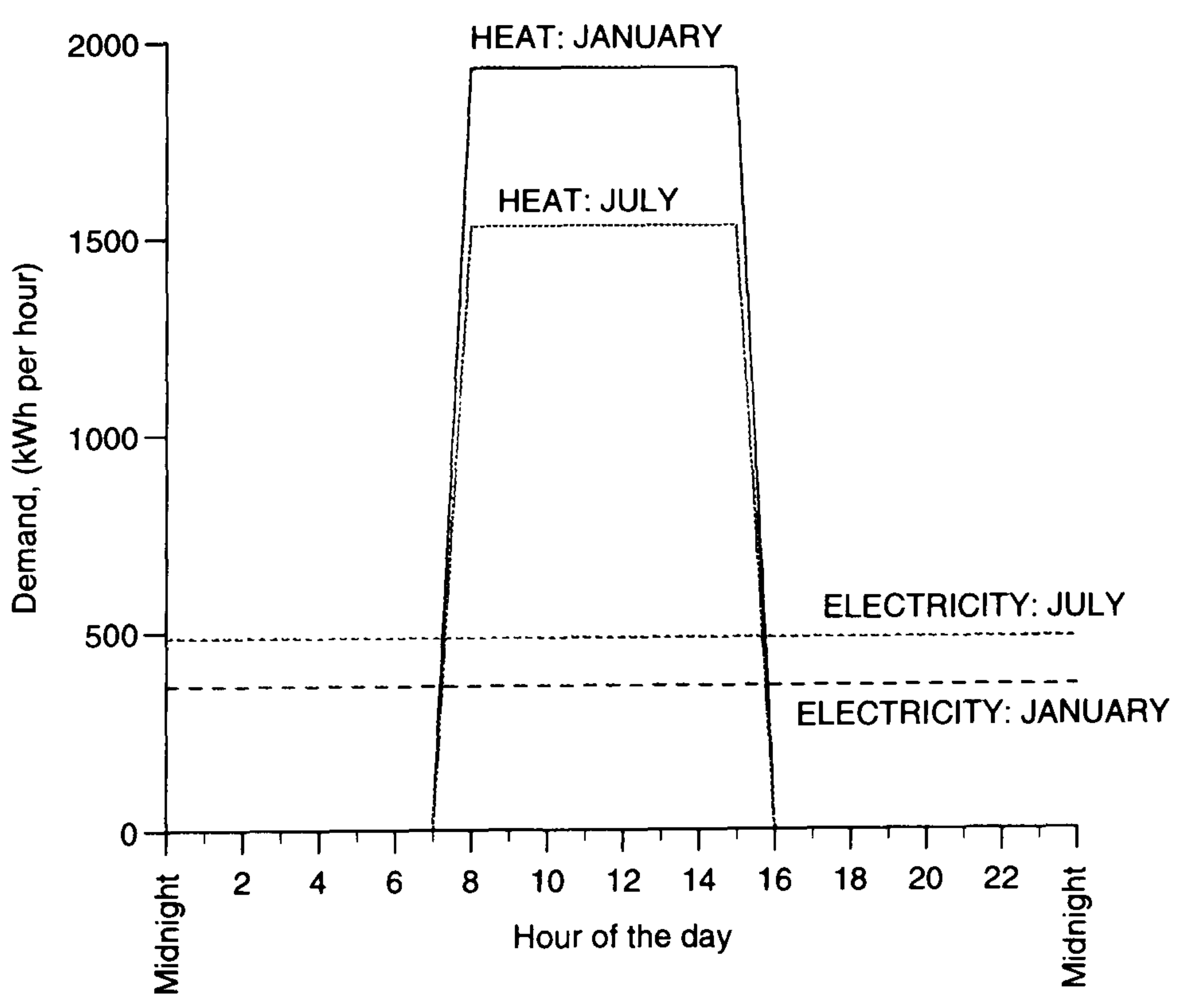


Figure 5.15: Hourly energy-demand profile for the slaughterhouse.

A combination of the shorter working hours in the building and a relatively low heat-to-power ratio produce what appears to be a good potential application for heat-storage. However, the heat-demand profiles have been simplified as a result of a lack of detailed data. The potential for heat-storage would result in the CHP unit operating for shorter periods which would then produce less electricity and a longer pay-back period for the investment.

CHP UNIT SIZE	YEARLY HEAT-STORAGE SAVINGS FOR CHP OPERATION AT:					
	PEAK PERIODS			OFF-PEAK PERIODS		
kW_e	Economic £	Heat MWh	CO_2 tonnes	Economic £	Heat MWh	CO_2 tonnes
220	6540	575	149	5086	447	116
255	7892	694	180	6139	540	140
385	12219	1074	279	9504	836	217
507	13813	1214	315	10794	949	247

Table 5.5: Predicted annual maximum savings produced as a result of the installation of the integrated system at the slaughter-house for a selection of CHP unit sizes

General observations from the results predicted by the model:
There are some features which are common in the case studies. For example, peak and off-peak heat-storage predicted financial savings will reach a maximum before decreasing as the size of the installed CHP unit is increased. However, this is not recorded in the results from the case of the slaughter-house. Increasing the size of the installed CHP units for each site will increase the levels of thermal-energy available for the heat-store. However, a larger unit will satisfy more of the demand for heat from each site and consequently lead to a reduction in the shortfall of heat supplied. This 'catch-22' can be overcome if the heat can be stored for longer time periods, when it would be able to satisfy the demand on a month-to-month basis.

The results produced have given a unique first-stage appraisal of the benefits of employing TES in CHP systems at the 5 sites. The results are not promising and do not yet include the associated costs for the storage system. CHP sizing methodology together with the relatively low unit value of heat are the two significant factors which will limit the economic potential of small-scale integrated CHP and TES systems. One significant obstacle to the increased financial value of the energy-store is the availability of low unit priced off-peak electricity. If this option were not available at a site, then the savings produced by operating the CHP unit at night will be increased, leading to an improvement of the economic viability of the proposed system. However, in the cases discussed, the increased savings will not be sufficient to produce an acceptable pay-back period. The displacement of CO_2 emissions indicated for each of the cases provides an environmental benefit over-and-above the use of CHP alone. This form of benefit is increasingly being publicised and should be considered in the full appraisal of energy investments.

5.4 A Detailed Case Study

Section 5.3 examined the theoretical potential for the proposed system at five test case-studies. The practical application of the system will now be appraised through the study of of a site where an installed integrated small-scale CHP/TES system exists.

An industrial sweet-manufacturing site has been selected for this investigation. It operates an integrated small-scale CHP and TES system. Operational examples of this type of system are rare because, typically, most small-scale CHP units are sized to supply the base heat-load and, hence there would be very little excess heat available for storage and reuse. The electricity demand of the manufacturing site has been steadily increasing over the last decade as the production output increased. In the late 1980s and early 1990s, the demand reached the maximum supply capacity. There were two options considered in order to increase the site's electricity-supply capability.

1 Pay for a larger supply to be installed by the local electricity company.
2 Pay a lesser sum to provide some form of on-site electricity generation.

When all the relevant factors had been considered, a decision was made to adopt the latter option and so install a small-scale integrated CHP and TES system.

Electricity and heat-demand - The manufacturing process requires the product to be dried for several days in specially dehumidified rooms held at 41°C. The total electricity consumption for the site during the year from August 1st 1994 to July 31st 1995 was 1,030 MWh. The daily electricity-demand profiles are shown in Figure 5.16. The main electricity-consuming units are: chillers, heaters and manufacturing-plant equipment. Most of the plant operates between 8.00 am and 4.30 pm, Monday to Friday, with packing and maintenance carried out in the evenings and on Saturdays.
The total annual-heat demand for the site between August 1st 1994 to July 31st 1995 has been estimated to be approximately 8,400 MWh. The main consumers of heat are the steam and hot-water radiators for the drying rooms; hot-water for the tap system and the cleaning of equipment and space heating. The heat sources are the steam boiler; the 70kW$_e$ CHP unit, the space heating boiler and nine electric heaters.

5.4.1 The Combined Heat-and-Power Unit.

A 70kW$_e$ and 120kW$_T$ gas-fired spark-ignition CHP unit has been modified and installed at the site. The unit was installed on a fixed-term contract with no initial capital outlay. Electricity and maintenance are supplied at 3.24p/kWh by the CHP energy-supplier and the gas is purchased separately at 25p/therm.
The CHP unit has been modified through the removal of the exhaust-gas heat-

exchanger, so that the overall heat-output is now reduced to 63.1kW. This, together with the installation of a dump-radiator were carried out to ensure that the unit will continue producing electricity through periods of little or no heat-demand. Without these modifications, the unit - which is modulated on the heat-demand of the site - would shut-down automatically during periods of low heat-demand.

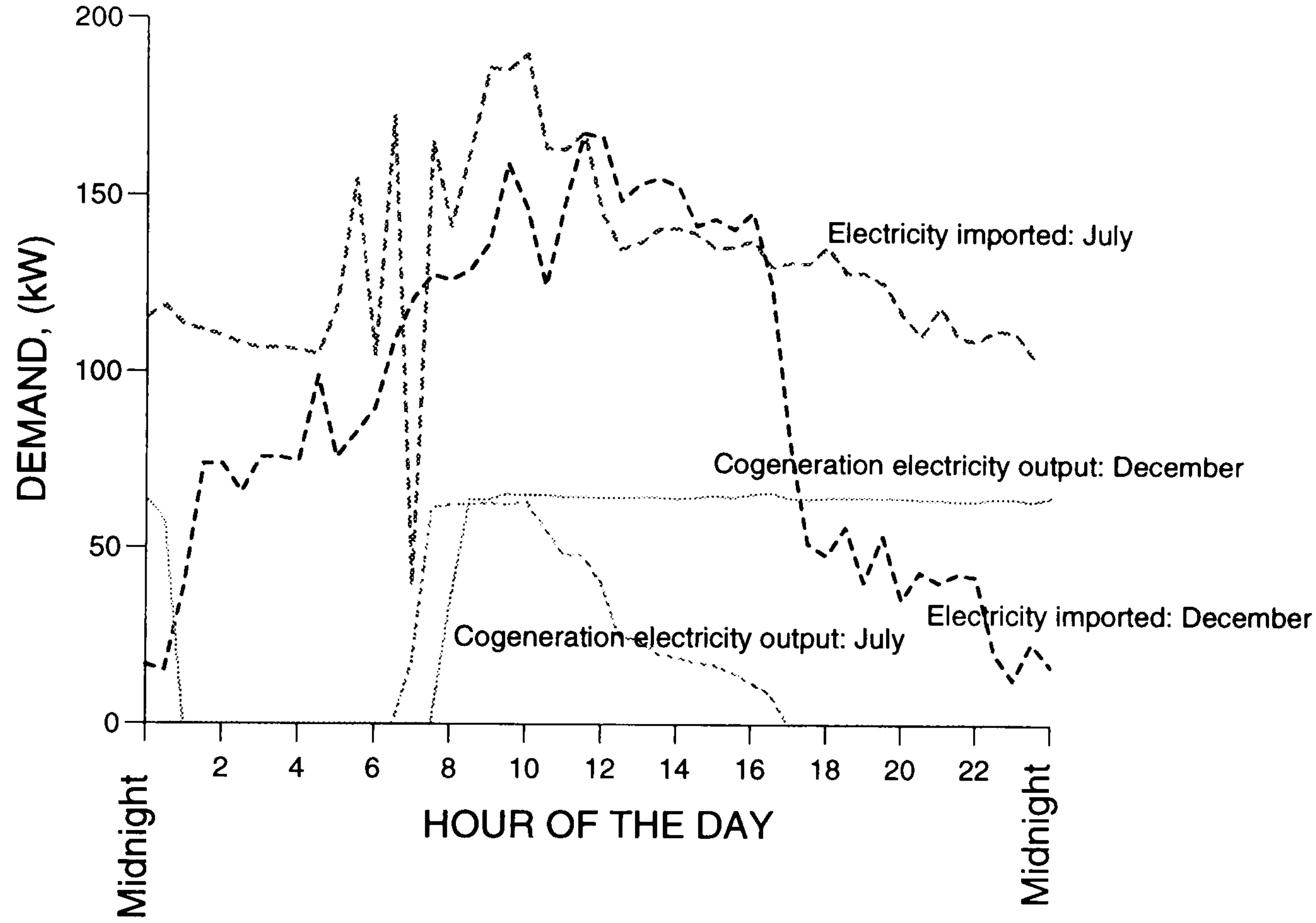


Figure 5.16: Manufacturing-site's electricity demand and CHP output profiles for December 1994 and July 1995.

Electricity and heat-output - The unit had been installed to operate for 17 hours/day, 6 days/week and 52 weeks/year, which amounts to a potential 5,304 operational hours per year. The unit produced 132,726 kWh of electricity in the period from August 1st 1994 to July 31st 1995 during 2,301 operational hours (i.e. an availability of 43%). 160 MWh of electricity would have been produced during the year if the CHP unit had not automatically shut down during March and April 1995 as a result of mechanical failure. The heat-output from the CHP unit closely follows the electricity output with 120 MWh of heat being produced during the year. This figure would have been approximately 145 MWh if the breakdown had not occurred. The potential maximum yearly heat-output - for the stated operating times - from the CHP unit is currently 335 MWh. This rises to 636 MWh with the inclusion of an exhaust-gas heat-exchanger.

The economics of the CHP unit.

Table 5.6 shows the gas cost per unit of electricity produced by the CHP unit for total heat-outputs of 63.1 kW and 120 kW. Given the current gas prices and the suppliers charge of 25p/therm and 3.24 p/kWh respectively, the CHP unit will operate at a cost of 5.24 p/kWh$_e$ (i.e. 2.00[1]p + 3.24p) whilst the unit's heat-output is held at 63.1 kW. This is only an ideal cost, as in practice the gas consumption is likely to be slightly higher when the unit operates on part-load, is incorrectly tuned or as the unit wears through use, thus lowering the overall electricity output. The current average marginal cost (for one year) of imported electricity at the site is approximately 5.9 pence/kWh (London Electricity), giving a profit of 0.66 pence per kWh$_e$ provided all 63.1 kW of heat produced by the CHP unit is utilised.

70kW$_e$ CHP Unit with an Hourly Fuel Consumption of 242kWh					
CHP Heat-Output	Cost to Operate (£/hour)	Value of Heat-Output (£/hour)	Gas Cost for Electricity (£/ hour)	Gas Cost p/kWh$_e$	Hourly CO_2 emissions from CHP, kg
63.1kW_T	2.06	0.66	2.06-0.66=1.40	2.00	47.2
120.0kW_T	2.06	1.25	2.06-1.25=0.81	1.16	47.2

Table 5.6: CHP gas costs per unit of electrical-energy produced .

Assumptions:
Gas price = 25p/therm, electricity costs 5.9 p/kWh from utility company, CHP supplier charge including maintenance = 3.24 p/kWh, steam boiler efficiency = 82%, average UK generating efficiency = 35% and the burning of one therm of natural gas (CH_4)will give rise to the emission of 5.711 kg CO_2 in the exhaust.
If the units heat-output is increased to 120 kW, then the situation will change as indicated in Table 5.6. The cost of gas for CHP and that for the imported electricity produced is now 4.40 p/kWh$_e$ (i.e. 1.16p + 3.24p), which provides a potential operational margin for profit up to 1.5 pence per kWh$_e$ generated.

5.4.2 Thermal Energy Use Analysis.

The schematic in Figure 5.18 shows the arrangements of some of the main components of the installed integrated CHP/TES system. In addition to the TES unit, the heat provided by the CHP system is only supplied to (1) the four 22kW$_T$ fan-blown drying radiators; (2) the 15kW$_T$ dehumidifier radiator and (3) the dump-radiator.

[1]2.00p is the cost of the fuel to run the CHP unit

70kW$_e$ CHP Unit with an Hourly Fuel Consumption of 242kWh			
CHP Heat-Output	CHP CO_2 emissions per hour, kg	Marginal cost of heat in terms of CO_2 emissions, kg/hour	Marginal cost of heat in terms of CO_2 emissions, kg/kWh$_T$
63.1kW$_T$	47.2	8.16	0.12
120.0kW$_T$	47.2	8.16	0.07

Table 5.7: CHP CO_2 emissions per kW$_e$ and per kW$_T$.

There are currently four drying-radiators connected in parallel, each with an output of 22kW$_T$ (corresponding a hot-water mass-flow rate of 1.85kg/sec) and a surface area of 600mm x 1400mm. The drying rooms are heated to a temperature of 41°C (for the intake air at 15°C). Plans exist to install further radiators, which would increase the demand for hot-water. The total energy-demand from these radiators over a one year period is estimated to be 477 MWh for the drying radiators and 80 MWh for the dehumidifier radiator, giving a yearly total of 557 MWh.

The dump radiator will radiate up to 50kW of heat, and is required to ensure that the CHP unit does not overheat, and consequently shut down during periods of low heat-demand. A 15 kW$_T$ radiator is used to preheat the air being fed to the dehumidifier unit: this will remove the moisture from the heated air before it is returned to the drying rooms. There are currently a minimum of 30 wash-basins located in the factory. The current daily-use of hot water is approximately 8 cubic metres, amounting annually to 66 MWh and 73 MWh for the hot water requirements of the tap-system and equipment wash-down, respectively. This water will pass through the TES unit: if it is not at the appropriate temperature, then it must pass through the heat exchanger in the angelery, where heat will be taken up from the returning condensate (via a shell-and-tube heat exchanger) in the steam-distribution system - see Figure 5.18. The full contents of the TES unit (i.e. 3,800 litres of hot water stored at about 60°C) is consumed in about one hour during the equipment cleaning process. Heat will continue to be supplied to the TES unit until the outlet temperature equals approximately the inlet temperature. In this case, water will be diverted to the dump radiator.

5.4.3 Integrated Small-Scale CHP/TES System.

The site's integrated CHP/TES system has the capacity to produce, store and consume in excess of 120 MWh of heat each year. The capital cost associated with the purchase and installation of the components of the TES system is relatively high compared with the cost of the CHP unit. In many cases, the CHP unit is not currently paid for by the customer directly, but rather through contract-supplied

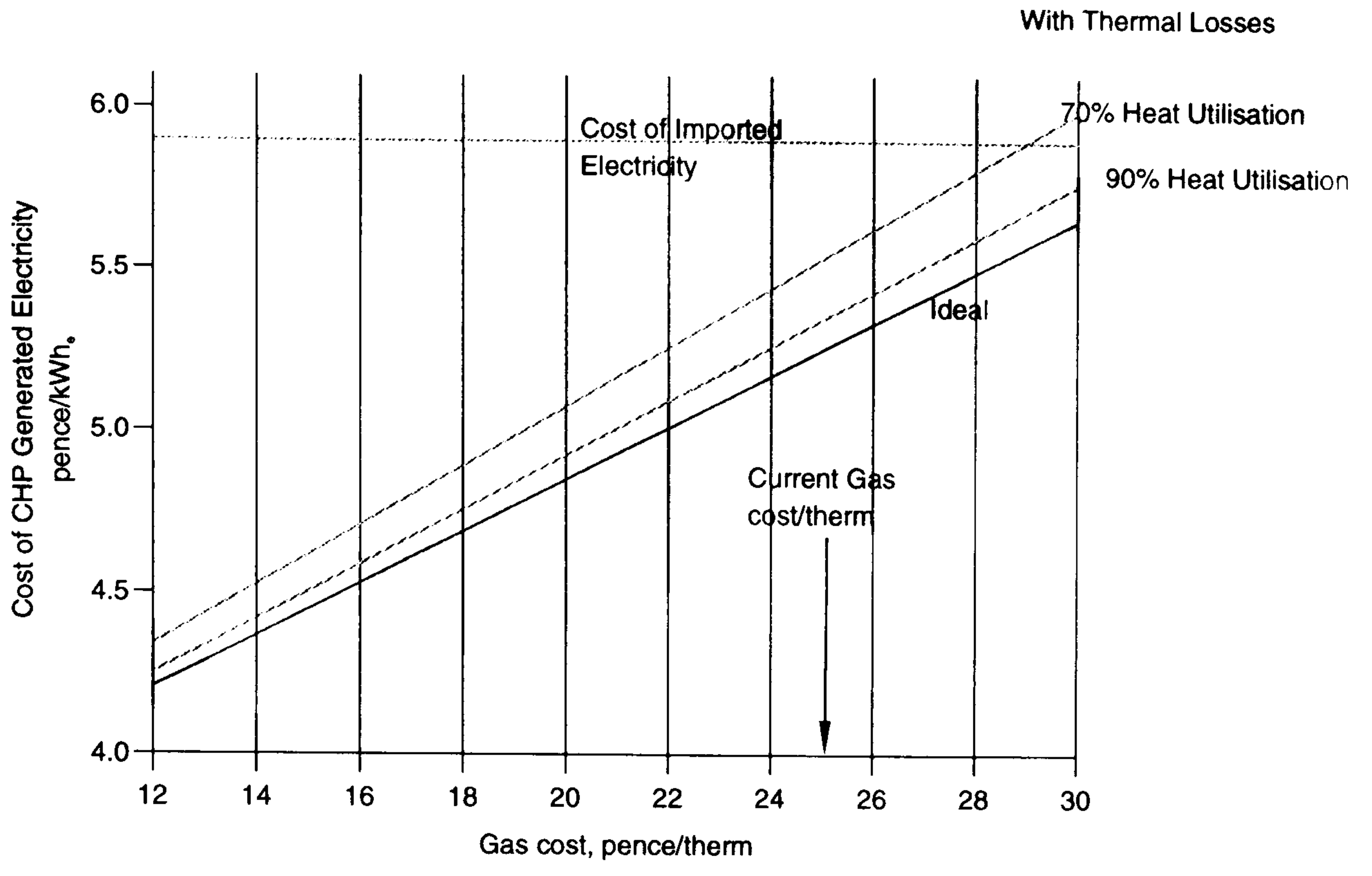


Figure 5.17: Variation of the unit cost for CHP-produced electricity with unit-gas costs.

electricity. The parts required for the total system include the TES unit, dump radiators, extended pipe-systems and an assortment of valves. The capital and installation cost of the full system amounted to more than £22,000. However, part of this work would have always been required, so the total additional expenditure for the installed TES system was over £12,000. In this case, this is likely to produce an unacceptably-long simple pay-back period exceeding two years - the acceptable figure for investments undertaken at this site - although three years is more common in this market. The CHP unit is currently set up with a heat-output of 63.1kW which will give a yearly ideal maximum output of 335 MWh of thermal-energy (operating 17 hours/day, 6 days/week, 52 weeks/year). If the exhaust-gas heat-exchanger is added, then this yearly total will rise to 636 MWh. This output is only slightly greater than the yearly heat requirements of the fan-blown radiators and is less than the total demand for heat (696 MWh) if the daily wash-down of equipment and the hot-water requirements of the tap system are also included.

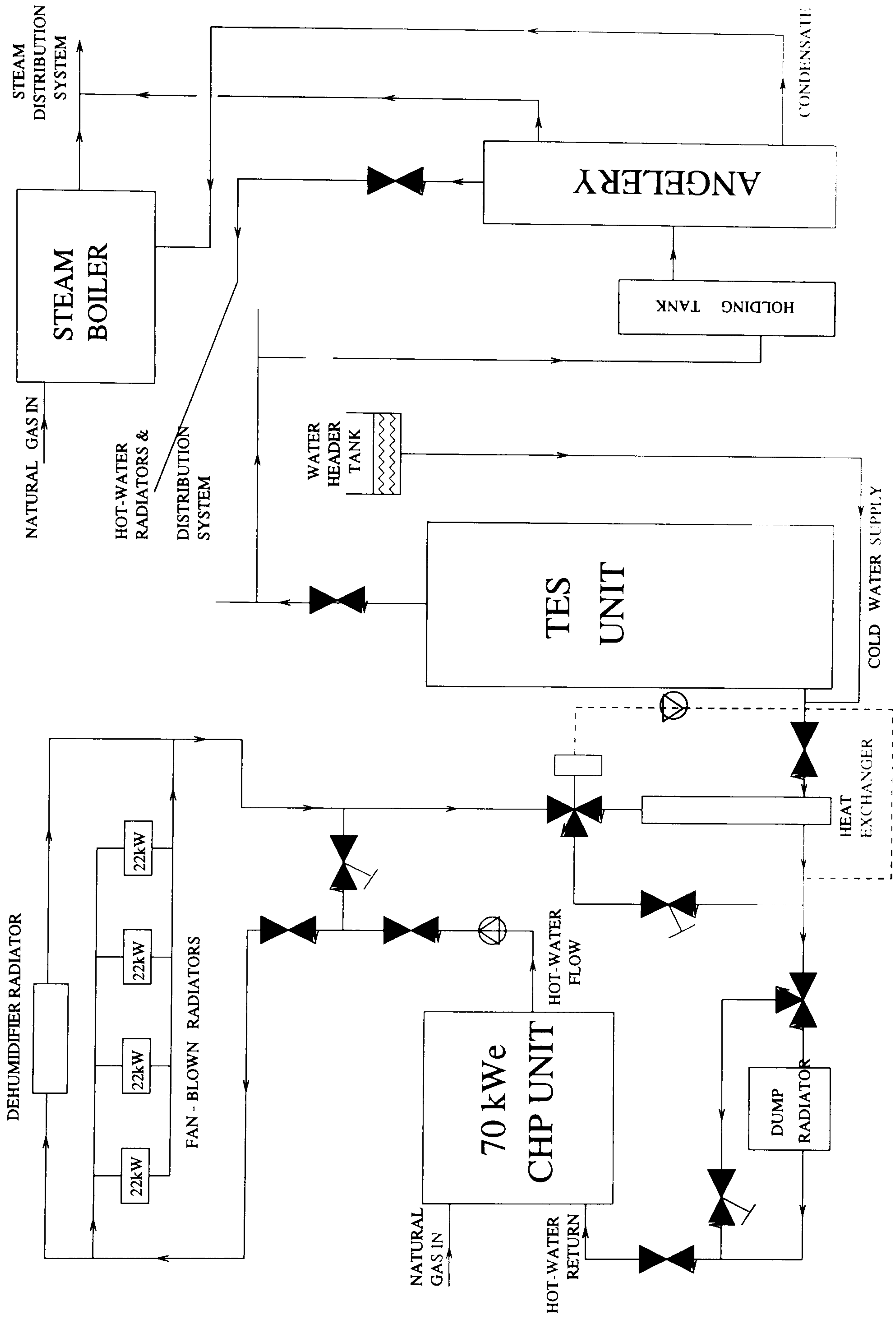


Figure 5.18: CHP hot-water distribution system and major components.

Observations and predictions.

The operational data for the CHP unit for the period from August 1st 1994 to July 31st 1995 have been obtained from the CHP unit's supplier and installer and examined in detail. During March and April 1995, the CHP unit was out of operation due to an alternator failure. Also the average electrical output of the unit was limited to between 63kW$_e$ and 66kW$_e$.

Four CHP/TES potential operating-configurations have been identified with the economic results shown in Table 5.8. These different operating conditions have been selected to represent the savings produced by the system when (i) actual historical data is used, (ii) predictions are made according to site energy-demand and (ii) alterations are made to the CHP unit to allow increased heat output. The four operating configurations are:

(1) The operational data for the period from August 1st 1994 to July 31st 1995.

(2) As in (1), however, the heat-and-electricity outputs for March and April 1995 have been estimated in line with the usual on-site demand.

(3) The current CHP unit operating at maximum output.

(4) Ideal output and fuel consumption, with the replacement of the exhaust gas heat-exchanger to the CHP unit.

Case 1 is calculated with the site records, whilst the other three cases involve a degree of estimation. The final column in Table 2 gives the degree of profit or (loss) for the system in monetary terms.

CASE		ANNUAL SAVINGS				COSTS	SYSTEM
	Electricity Output from CHP unit (kW$_e$)	Heat Stored from CHP unit Output (kW$_T$)	Heat for drying (kW$_T$)	Total Value Heat + Electricity £	Total CO_2 Saved (tonnes)	CHP Running Costs £	PROFIT/ (LOSS) £
1	132,726	59,821	59,821	9,076	15.5	9,447	(371)
2	160,000	71,821	71,821	11,054	17.6	11,388	(334)
3	344,760	122,500	188,271	23,573	29.8	22,979	594
4	371,280	122,500	513,614	28,524	29.8	22,979	5,545

Table 5.8: Performance of the integrated CHP/TES system for four different operating conditions for a one year period.

Operational case 1 - On an annual basis over 59.8 MWh of heat can be usefully utilised in the TES unit which will displace approximately 14.5 tonnes of CO_2 emissions. At the given energy prices this will correspond to savings of over £620 (approximately 1.4% of the gas bill) in a one year period. The application of the TES unit saved energy and improved the economics of the CHP system through the increased utilisation of more of the waste-heat produced. The utilisation of the TES unit also allowed the CHP unit to produce electricity for longer periods. and at a higher level of output than otherwise would have been possible without installation. It was not possible to determine this figure exactly as the operating history of the hot-water radiators and TES unit are not known individually. Therefore, the TES unit's use pattern was estimated according to the predicted operation times of the units as stated by the site's energy manager. This system results in an overall loss of £371 per year.

Operational case 2 - When the shortfalls in heat and electricity production during March and April 1995 are accounted for, and gas consumption increased pro-rata, the systems costs increase and the result is a yearly loss of £334 The energy value of the TES unit has now increased to 71.8 MWh (equivalent to £807 and 17.6 tonnes of CO_2 emissions) in line with the increased heat-output from the CHP unit.

Operational case 3 - The theoretical yearly maximum heat-output at this site for the CHP unit operating with a rating of 63.1 kW_h is 334,682 kWh, when functioning for 17 hours/day and 6 days/week all year round. The yearly energy saved as a result of the utilisation of the TES unit amounts to 122.5 MWh - displacing almost 30 tonnes of CO_2 - with an economic value of £1,274. Note that, the heat-output is not shared equally between the TES unit and the drying radiators. The system now operates with a yearly profit of £594.

Operational case 4 - If the heat-output from the CHP unit is increased via the addition of the exhaust-gas heat-exchanger, then the total heat-output would rise by 56.9kW_T to 120 kW_T. This would be equivalent to an additional 302 MWh of heat annually. If this heat displaces thermal-energy from the steam boiler (of efficiency 82%), then the annual saving would amount to £3,139 at current given energy rates. The system arrangement now shows a yearly operational profit of over £5,500. Even without the TES unit, the system would be expected to show a profit. As the heat output from the CHP unit increased, the energy and monetary savings achieved through the utilisation of TES unit peaked at 122.5MWh (displacing 29.8 tonnes of CO_2 emissions) and £1,274 respectively, which corresponds to the maximum demand for indirect hot-water at the site. The value of the energy stored in the TES unit contributes significantly towards the overall profitability of the system. If this system is introduced, then an additional heat-sink of some type (i.e. radiator or TES) will be required to ensure that the maximum electricity output is maintained. The additional costs of these units will be approximately £500 for the radiator and £5.000 for the additional TES unit.

5.4.4 Case Study Summary.

The four different cases have been documented to show how changes to the existing integrated CHP/TES system (i.e. in cases 1 → 4) might improve its viability. Two of the four cases show that the CHP/TES system is costing more to operate than if the heat and electricity were produced separately from the grid and steam-boiler for the current given unit energy-prices. However, in all cases, the value of the additional heat stored and utilised (without losses) via the TES unit leads to savings of between 59.8MWh (£620) and 122.5 MWh (£1,274) annually - namely 1.4% to 2.8% of the site's annual gas costs assuming negligible heat losses - which significantly improves the overall economics of this system. This will correspond to a reduction in CO_2 emissions of from 14.5 tonnes to 29.8 tonnes annually. It should be noted that this site is not a typical one for the installation of a CHP system. These savings could be a convincing factor for potential investors in CHP if it were not for the significant capital costs and ensuing long associated pay-back periods involved in the purchase and installation of the system.

5.5 Integrated CHP & TES: Future Work & Potential-Prospects

The application of integrated small-scale CHP and TES systems is limited by the four factors already documented. An exception whereby small-scale integrated CHP/TES systems appear more valuable - on an energy, environmental and economic basis - is in their application to greenhouses. These systems can have the added advantage of the recovery and the use in greenhouses of the CO_2 in the exhaust gases; the CO_2 being used for enhanced growth rates in the crop. This is one area which provides interesting potential. TES allows heat stored during the day to be used after dark to heat the greenhouses. CHP units have a lower heat output - for each unit of CO_2 produced - than gas-fired boilers. This is an significant advantage because it is not always possible to utilise all of the heat from the boilers, especially during the summer. Initial savings produced by these systems appear promising, but a full documentation of a system as a case study will be necessary to verify the early promise.

TES technology would probably be better directed towards - and utilised by - other more appropriate energy systems, such as solar power, where solar radiation, wind or tidal power, which provide apparently unlimited quantities of energy at intermittent times and for varying periods.

5.6 Summary

A study of the energy, environmental and economic potential for an integrated small-scale CHP and TES systems has been undertaken. There were four main obstacles to the beneficial application of TES to small-scale CHP systems, namely: (i) the current commonly employed CHP unit sizing methodology; (ii) the high capital and installation costs of the TES systems; (iii) the relatively low economic-value of heat (at present utility rates) and (iv) the ready availability of low priced off-peak electricity at most sites. The documentation of how one example of an actual application of the system in industry displayed how the consumption of primary fuels could be reduced, with a corresponding reduction in the production of the greenhouse gases - primarily CO_2. For small-scale CHP systems to be energy-efficient and economically viable, it is necessary that the maximum amount of heat and power is utilised directly. As a consequence of this, CHP systems will normally be sized to satisfy the base heat-load and will modulate on thermal-demand, with the opportunity of importing or exporting any shortfall or surplus of electricity. In order to provide a cost-effective system, the properly sized small-scale CHP unit will rarely provide excess heat for storage. This fact has been firmly demonstrated in the first five cases documented in this study. Only in exceptional circumstances (e.g. when cost savings are not the main priority for the investor or when the demand for heat is extremely peaky or intermittent) will the economic potential for thermal-energy-storage arise. Even under these circumstances, it is likely that the capital costs for the purchase and installation of the TES unit will lead to an extremely long pay-back period or in many cases no cash pay-back at all. The industrial case-study examined, indicated that the pay-back period for the TES system of 9 years was achievable, assuming the maximum operating conditions presented in case 3.

In conclusion, it would seem that TES is generally not the most appropriate technology to apply to small-scale CHP systems. TES hardware, capital and installation costs are generally high. This is because a new and site-specific system will usually have to be designed and installed with no financial savings achieved on account of the scale of production. Additionally, the small-scale systems - by definition - produce relatively small quantities of power and it follows that spare heat-storage capacity will be limited.

CHP manufacturers and industry observers, may comment that a more cost effective investment would be to spend more time and effort in the correct sizing, operation and maintenance of new and existing small-scale CHP systems. In part this could be achieved through more detailed study of a potential site's current (and likely future) energy demand profiles and equipment operation, before the CHP unit is selected.

Chapter 6

CHP and Absorption Chillers

Introduction

In the United States, Canada, Japan and to some extent in central and southern Europe, where the climatic conditions are more extreme than in the UK, air conditioning during summer is considered equally important to heating during the winter. Over the last two decades, the UK's demand for space cooling has increased in line with greater levels of insulation and the addition of computers, monitors, faxes and other heat emitting equipment. In recent years, vapour-compression systems are increasingly being replaced by less environmentally damaging absorption systems. This is especially the case in Japan, where absorption-cooling capacity increased by over 100% in the four years to 1993.

In the preceding chapters of this thesis, consideration has been given only to applications where the main use for the CHP heat is for space heating. However, applications where one of the main requirement is to reduce the environments temperature below the ambient by refrigeration are also common. This chapter examines the ways in which the waste heat from small-scale gas-fired CHP units can be usefully employed - in an economically viable way - for winter heating and summer cooling via the incorporation of an integrated CHP/absorption chiller system. Cooling technology is described together with the theory of absorption systems, before the operational complexities involved with the integration of the two technologies are examined in detail. Optimising the proposed integrated small-scale CHP and absorption system requires the matching of both systems.
Two different cases are studied in order to highlight the salient points concerned with the integration of the two technologies. The first study examines the potential for the installation of the integrated system at a local hospital where small-scale CHP is already in use. A predictive model is developed so that the economic potential can be quantified. The second case-study examines the carbon dioxide (CO_2)

emissions from a CHP and absorption chiller system versus a conventional vapour compression cooling-system installed and operational at a site in the South-East of England. The emissions are first determined for standard and ideal conditions, before the effects of operational variations are assessed.

6.1 Cooling Technology

The Romans were among the first humans to employ a basic form of space cooling by exploiting a simple form of evaporative cooling. The effect is achieved by passing air over a pool of water, which causes the water to evaporate, provided that the air itself is not saturated with water vapour. On evaporation, the enthalpy of vaporisation is supplied from the residual bulk of the water, thus causing its temperature to decrease. This cooled water can then be used to reduce the temperature where required. The principles of refrigeration were further demonstrated by Faraday in 1824 via an experiment with a bent glass tube charged with ammonia and silver chloride. The year 1861 saw the patenting of Dominique Nicolle's ice-making machine, which brought the existence of the technology to a much wider audience [44]. There are now, in the 1990s, numerous ways of reducing the ambient temperature to satisfy demand requirements for space cooling: the two which are most widely used are the vapour-compression process and absorption-cycle refrigeration. Vapour-compression systems are by far the most commonly employed of all refrigeration systems and are most frequently used for air-conditioning and refrigeration. Absorption systems are used to a much lesser extent and become more viable when a cheap source of heat is available.

6.2 Absorption chiller systems

The application of absorption for the purpose of cooling has been a viable technology for more than a century; the first absorption machine (using ammonia as the refrigerant and water as the absorbent) being developed by a Frenchman, Ferdinand Carre in the mid-nineteenth century [92]. The use of absorption systems is increasingly rapidly throughout the world with a few significant countries leading the way. A good indication of the potential of these systems is demonstrated in Japan where almost 75% of Japan's large new buildings use absorption air-conditioning systems [93]. Absorption-cooling differs from vapour-compression systems in that the input energy will be in the form of heat as opposed to mechanical work for the latter case. This means that absorption systems can offer greater flexibility to the user as the heat can be supplied in a variety of forms. Both systems have an evaporator, a condenser and expansion valves. However, the electrically-powered compressor is replaced by an absorber, solution pump and heat source. These parts in the absorption system perform the same function, in so far that it receives a low-temperature, low-pressure refrigerant from the evaporator and conveys the refrigerant to the condenser at high pressure and high temperature.

The coefficient of performance (COP) of a refrigerator is a parameter used to indicate the effectiveness of the cooling system, and is defined by:

$$COP = \frac{Cooling\ Delivered}{Energy\ Input} \tag{6.1}$$

The COP for a vapour-compression system is typically five or six times that of an absorption system. While the COPs for vapour compression systems are higher than those for absorption systems, vapour-compression systems will usually require a higher grade of energy to power them (i.e. electricity versus natural gas, recovered heat or solar radiation as the input energy). Therefore, when comparing the COPs of the two systems, it is important to account for the differences in the cost of energy required by each. It should be noted that the energy requirement to operate the cooling fans, circulating pumps and other auxiliary energy use is not included in the COP ratings. However, these energy costs must be included in a full economic analysis of any proposed system. Consider the following example which illustrates these points:-

Example: COP of vapour-compression unit = 5.5 and the COP of an absorption chiller unit = 1.0

Each unit must produce 100kWh of cooling. If the cost of electricity is more than 5.5 times the cost of heat then the absorption chiller will have an operating cost advantage. However, if the cost of operating the auxiliary equipment is also included in the calculation, then the electricity will need to be more than 8.3 times more than the cost of heat before the absorption chiller system is cheaper to operate than the vapour compression system [17]. Another significant benefit of absorption chiller systems is that they are CFC free. The Montreal Protocol had an immediate effect on the use of refrigerants CFC 11 and CFC 12 which are used in centrifugal chillers. These substances have Ozone Depletion Potentials (ODPs) and Global Warming Potentials (GWPs). CFCs are several thousand times more environmentally damaging than CO_2. Other refrigerants have been developed to replace CFCs, which are less environmentally damaging. However, they are still several hundred times more damaging than CO_2. Additionally, with the new refrigerants, the efficiency of the compressor unit drops and this can lead to up to 25% less chilled water [94]. The use of CFC free absorption systems will stabilise/reduce the cumulative and detrimental effects on the environment produced by centrifugal cooling.

6.2.1 Types of absorption chillers

There are two main types of absorbent-refrigerant mixtures which are currently in common use: lithium-bromide (LiBr)-water and aqueous ammonia systems (AARs). In a LiBr-water absorption system, the LiBr is the absorbent and water is the refrigerant. In an AAR system, the water is the absorbent and ammonia is the refrigerant. Other refrigerant-absorbent mixtures exist, but are not commonly used in commercially-available absorption systems.

LiBr systems are categorised by the number of times (i.e. effects) the solution is heated to produces refrigerant vapours. LiBr-water absorption systems are referred to as single- or double-effect machines.
The COP for a single-effect system is typically two-thirds that of a double-effect system because a double-effect machine makes more use of the input energy. The COP of an absorption chiller will vary according to the type of system employed, as well as the temperatures of the recovered heat and of the chilled fluid. COPs for single-effect absorption chillers lie in the range from 0.6 to 0.7, whereas, the COP for a double-effect system will fall between 0.9 and 1.2 [95].

Single-effect absorption systems - There are two main configurations for single-effect absorption machines: where (i) the entire process is housed within one shell, or (ii) there exists a separate shell for the condenser and generator sections of the absorption machine. Simplicity of design, including only a few moving parts, helps give this type of unit reliability.

Double-effect absorption systems - A double-effect absorption machine has two stages of generation to separate the refrigerant from the absorbent. The temperature of the heat source required to drive the high stage generator must be higher than that used for a single-effect machine [17].
The heat input requirements and the cooling-output temperatures attainable vary between and within each system type.

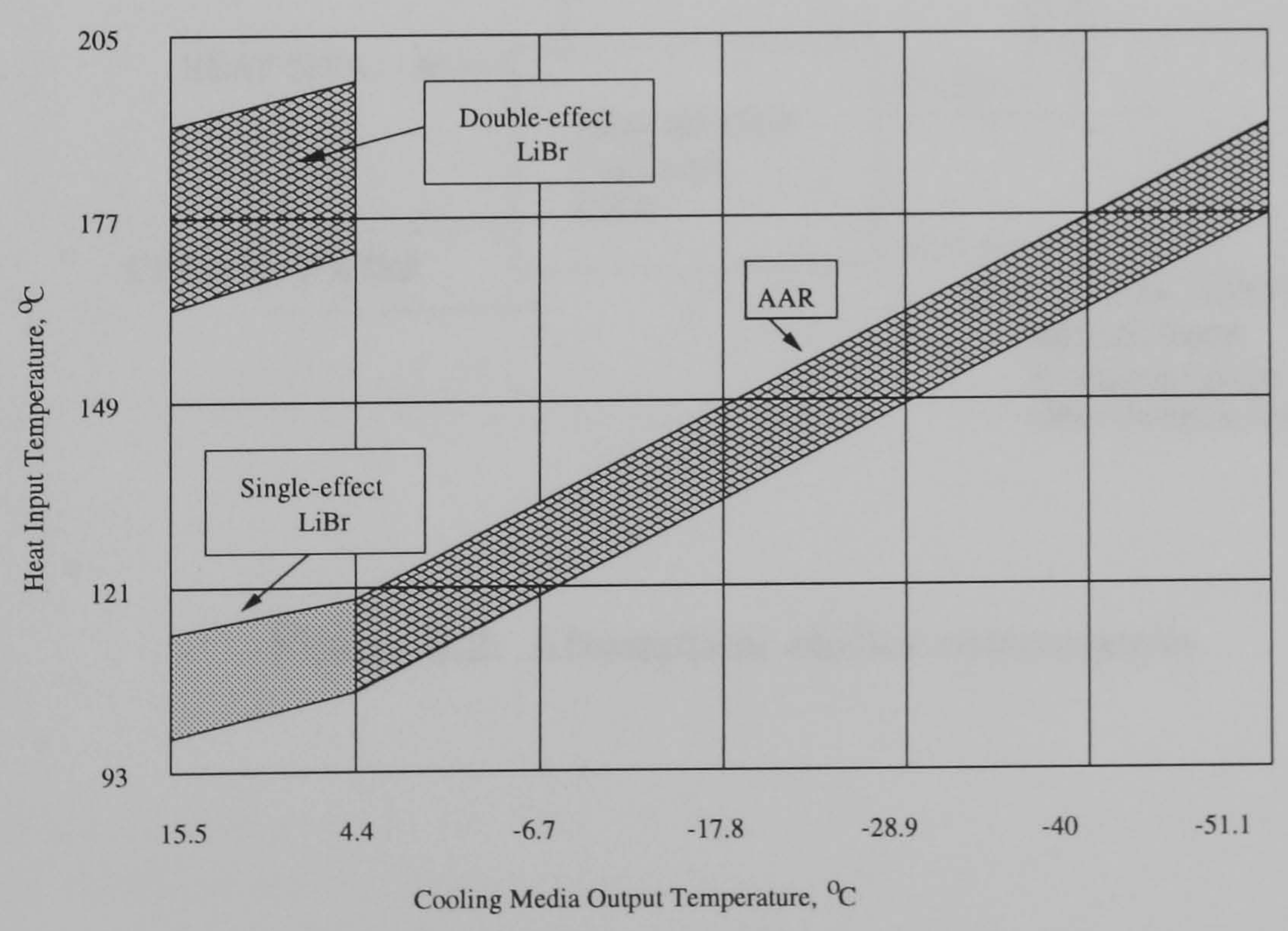


Figure 6.1: Absorption chiller input/output.

A LiBr-water system is typically the best match for cooling applications down to between 4°C and 6°C while an aqueous ammonia system is more appropriate for refrigeration applications down to −51°C. In spite of double-effect absorption systems being more expensive than single-effect machines, they will usually be selected in preference to single-effect units whenever there is a heat source with a temperature sufficient to power a double-effect machine. Both systems have different and unique requirements and outputs - see Figure 6.1.

6.2.2 Absorption Refrigeration System and Components - single-effect

The absorption refrigeration system has four major components:

1. The LiBr-water cycle.
2. Cooling tower and cooling-water system.
3. The chilled-water system.
4. The electrical components including the solution and refrigerant pumps.

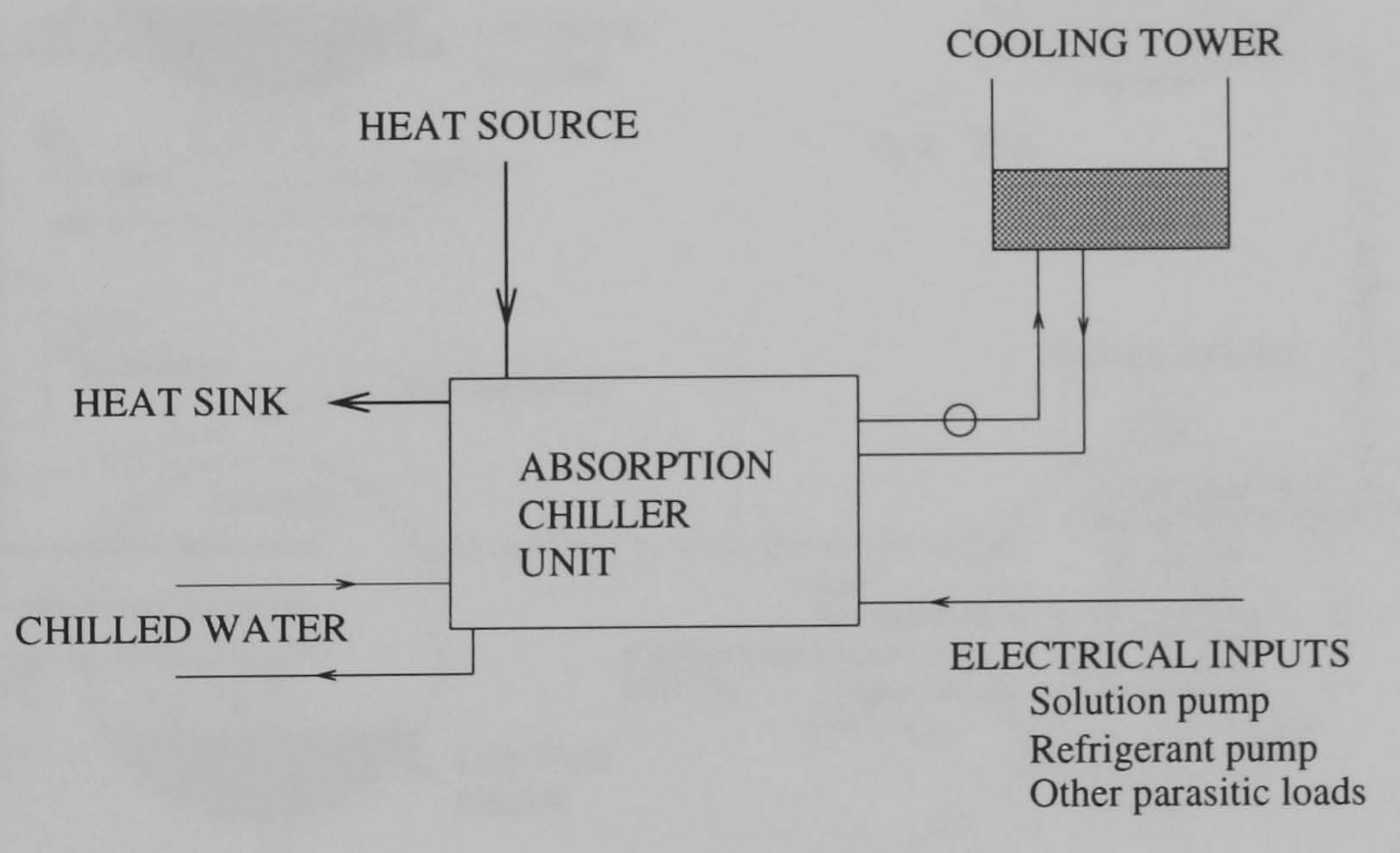


Figure 6.2: Absorption chiller components.

The Single-effect LiBr-Water Absorption Cycle

Water is used as the refrigerant in a water/Li Br absorption chiller - see Figure 6.3. The water is sprayed and evaporated at about 3 to 4°C in an evacuated vessel (the evaporator being maintained at approximately 0.01 Bar) onto a tube bundle through which the buildings chilled-water is circulating, thereby taking heat from it. The water vapour is drawn into the absorber section by low pressure resulting from the absorption of the refrigerant into the absorbent (i.e. the lithium bromide salt-solution). In order to expose a large amount of LiBr solution surface to the water vapour, the solution is sprayed over the absorption tube bundle. The degree of affinity of the absorbent for the refrigerant is a function of the solution concentration and temperature. The lithium-bromide salt-solution is then pumped to the generator (at a pressure of 0.1 Bar) where it is heated - the source temperature can be as low as 80°C if there is enough time - in the generator to reduce the humidity. The water vapour is finally condensed (in the condenser) using cooling water from a cooling tower. The re-liquefied water drains back into the first vessel, evaporates again, and the process is repeated.

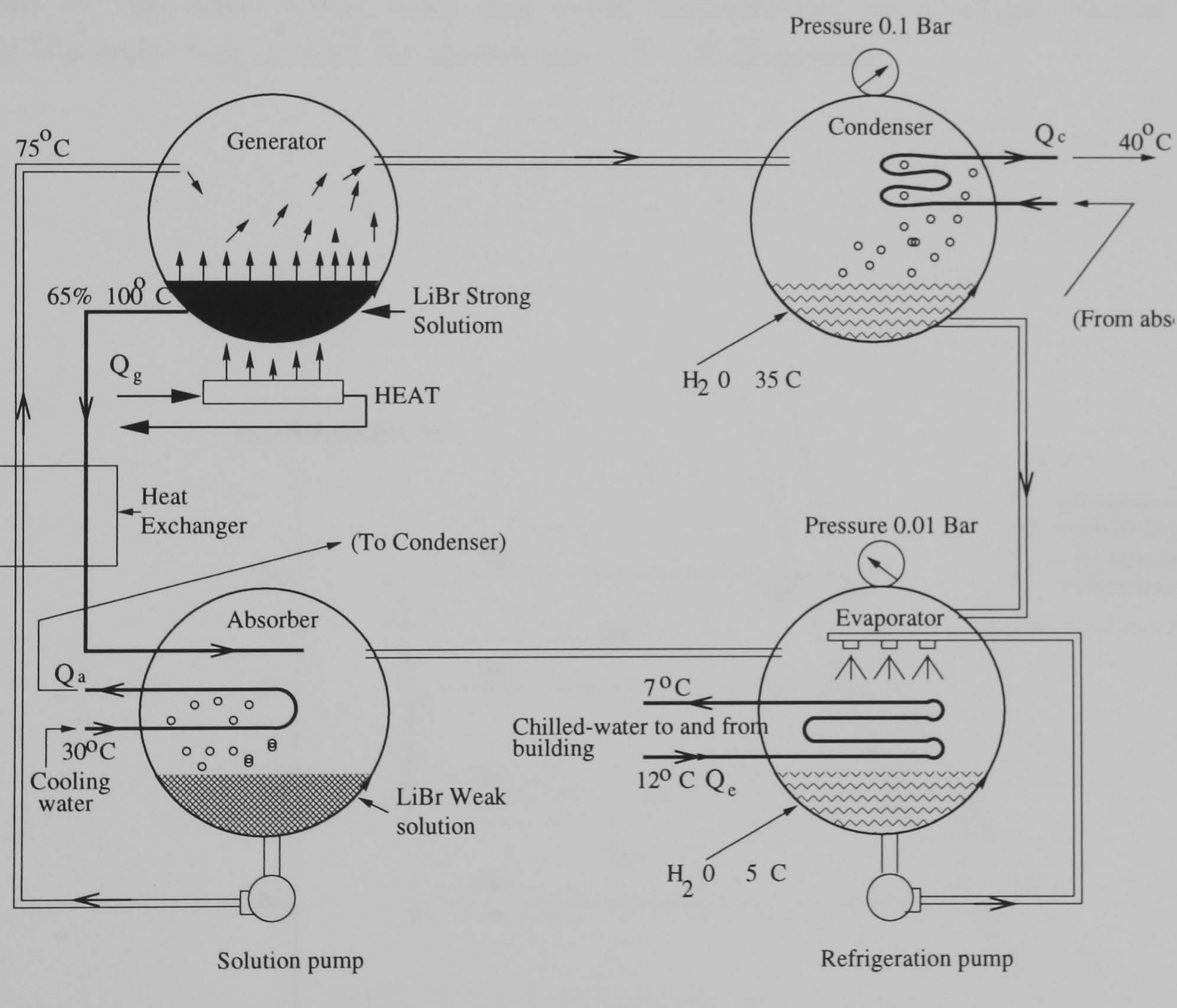


Figure 6.3: Absorption cycle.

An additional component to the system is the solution-heat-exchanger. It preheats the solution on its way to the generator using the hot solution coming back from the generator. This increases the efficiency of the overall absorption cycle. One additional phenomenon is the 'heat of reaction' in the absorber. When the LiBr salt solution absorbs the water vapour, the heat picked up in the evaporator is given off, but but it must be disposed of. This heat is removed by the cooling water as it comes back from the cooling tower.

Another important part of the absorption chiller is its purge. The effectiveness of the machine depends on the un-obstructed flow of water vapour from the evaporator to the absorber. If air or other gas resulting from the absorption process is present, this makes it more difficult for the water vapour to be absorbed by the LiBr solution. A 'purge' system must be an integral part of the operation. It must continuously remove any air which may enter the machine or any gas which may be produced. Because air in an absorption machine would result in corrosion of the inner steel surfaces, the purge is also designed to avert that.

Ideal absorption-cycle

An understanding of the principles of operation of the ideal absorption cycle will aid the understanding of the operation of real cycles. Figure 6.4 illustrates the operation of the ideal cycle with the cycle represented as a single closed line, which is the only way it can be shown on a T - S diagram.

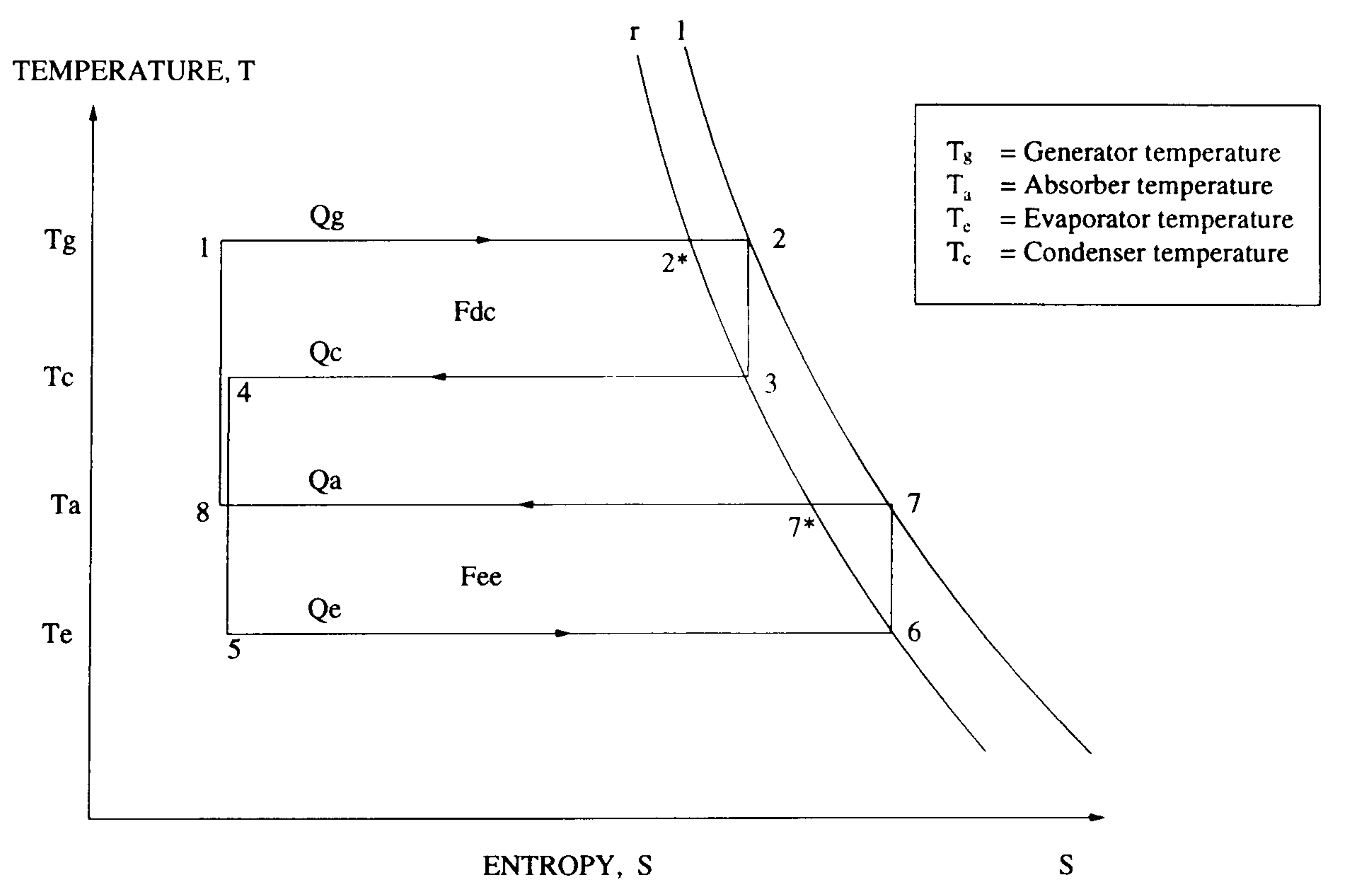


Figure 6.4: Single-stage, idealised absorption cycle on the temperature-entropy linear-scale plot.

1-2-3-4-1 represents the driving cycle (i.e the Carnot cycle)
5-6-7-8-5 represents the cooling cycle (i.e. the reverse Carnot cycle)

The work of the two sub-cycles F_{dc} and F_{cc} are equal and therefore the four process temperatures cannot be arbitrarily chosen but are related by:

$$T_e T_g = T_a T_c \tag{6.2}$$

The ideal COP (for the reversible cycle) is:

$$COP = h_{fg}/(h_{fg} + \Delta h_s) = T_e/T_a = T_c/T_g \tag{6.3}$$

If the temperature ratios are considered, it is clear that the limiting value of unity is the maximum COP that can theoretically be achieved for a single-stage unit. Additionally, in order to maximise the COP, both the evaporator and absorber temperatures will have to be nearly equal. This is similar to that for vapour-compression cycle, where the COP of the Carnot ideal cycle improves as the hot and cold source-temperatures converge.

A high generator-temperature will not have any effect on the ideal cycle other than elevating the condenser temperature. In a real system, the COP will decrease although a smaller chiller could sometimes be selected due to the increased temperature difference in the generator and condenser.

The single-stage absorption process:

8-1: Isentropic heating of the refrigerant in the solution.
1-2: Heat introduced into the generator
Heat of evaporation
$h_{fg} = (S_1 - S_2)\, T_g$
and heat of solution
$\Delta\, h_s = (S_1 - S_{2*}\, T_g$
2-3: Isentropic cooling (i.e. at constant ρ) down to the saturation temperature T_2 of the generator's super-heated vapour.
3-4: Condensation
4-5: Isentropic cooling of the refrigerant (under constant pressure)
5-6: Evaporation
6-7: Isentropic heating of the saturated vapour (at constant pressure)
7-8: Absorption by the solution of the super-heated vapour (of state 7). Both the heat of solution and the heat of evaporation h_{fg} are liberated.
$h_s = (S_7 - S_{7*})\, T_a$
$\Delta\, h_{fg}(S_{7*} - S_8\, T_a$

Real absorption cycles

Because a LiBr absorption chiller uses a refrigerant absorbent solution instead of mechanical compression to transform the low-pressure refrigerant vapour to a high-pressure refrigerant vapour, a pressure-enthalpy (P-H) diagram cannot be used to show graphically the absorption cycle. Instead a PTX equilibrium chart - see figure 6.5 - which includes solution concentration has been developed.
One hazard for LiBr-water systems is crystallisation, which occurs when the solution freezes and is a frequent cause of unscheduled down time and maintenance calls. This blocks passageways and stops the refrigeration process, which in turn stops the cooling effect. From figure 6.5, it can be seen that crystallisation occurs for a range of solution temperatures and solution concentrations. Clearly the higher the concentration and the lower the temperature, then the likelihood of crystallisation occurring increased. The main reasons for the occurrence of crystallisation are: malfunction in the air-conditioning system, failure of a pressure-reducing valve or electrical failure. When Direct Digital Controls (DDC) systems are installed, then the problems associated with crystallisation are substantially reduced.

Factors which influence the outputs from LiBr-Water absorption chillers

(1) Solution temperature

(2) Solution concentration

(3) Refrigerant's temperature

(4) Refrigerant's vapour-pressure

Variations in chiller performance

Figure 6.6 illustrates how changes to the inlet water temperature to the absorption chiller significantly influence the cooling capacity of the chiller. It indicates that low source-water temperatures will require the use of larger and more expensive absorption chillers in order to achieve the same cooling-effect. Further variations to the cooling output of the absorption chiller can be observed in Figure 6.7, which shows the effect of changes to the cooling water temperature on the units cooling-capacity. Both of these factors will have a direct effect on the COP of the chiller unit. Another significant factor for COP and the unit's cooling-capacity will be the required temperature of the chilled water. It is clear that each of the above factors will be significant when determining the environmental benefits - in terms of CO_2 emissions - produced through the application of absorption chillers for space cooling.

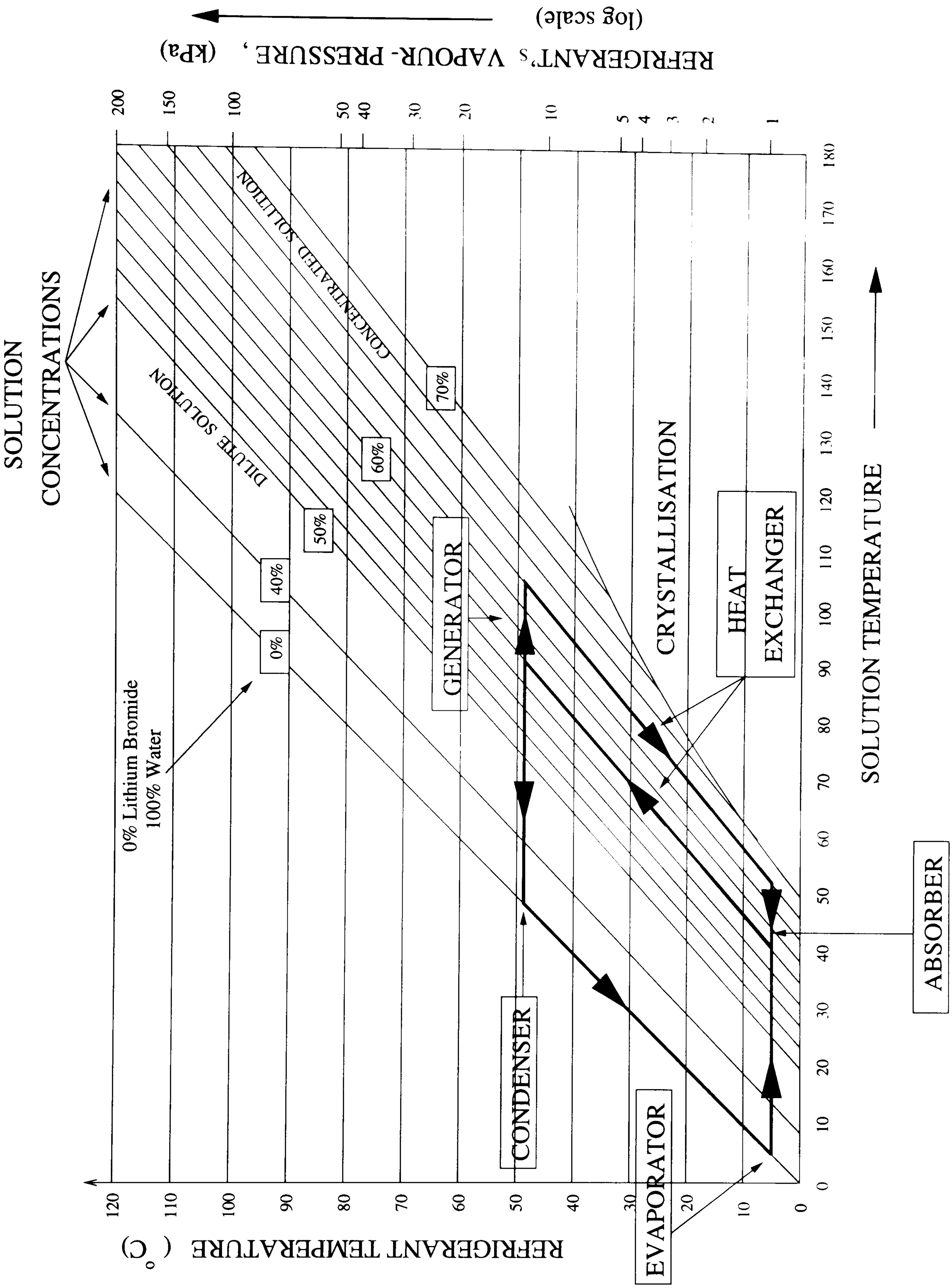


Figure 6.5: Single-stage real cycle on the PTX diagram [13].

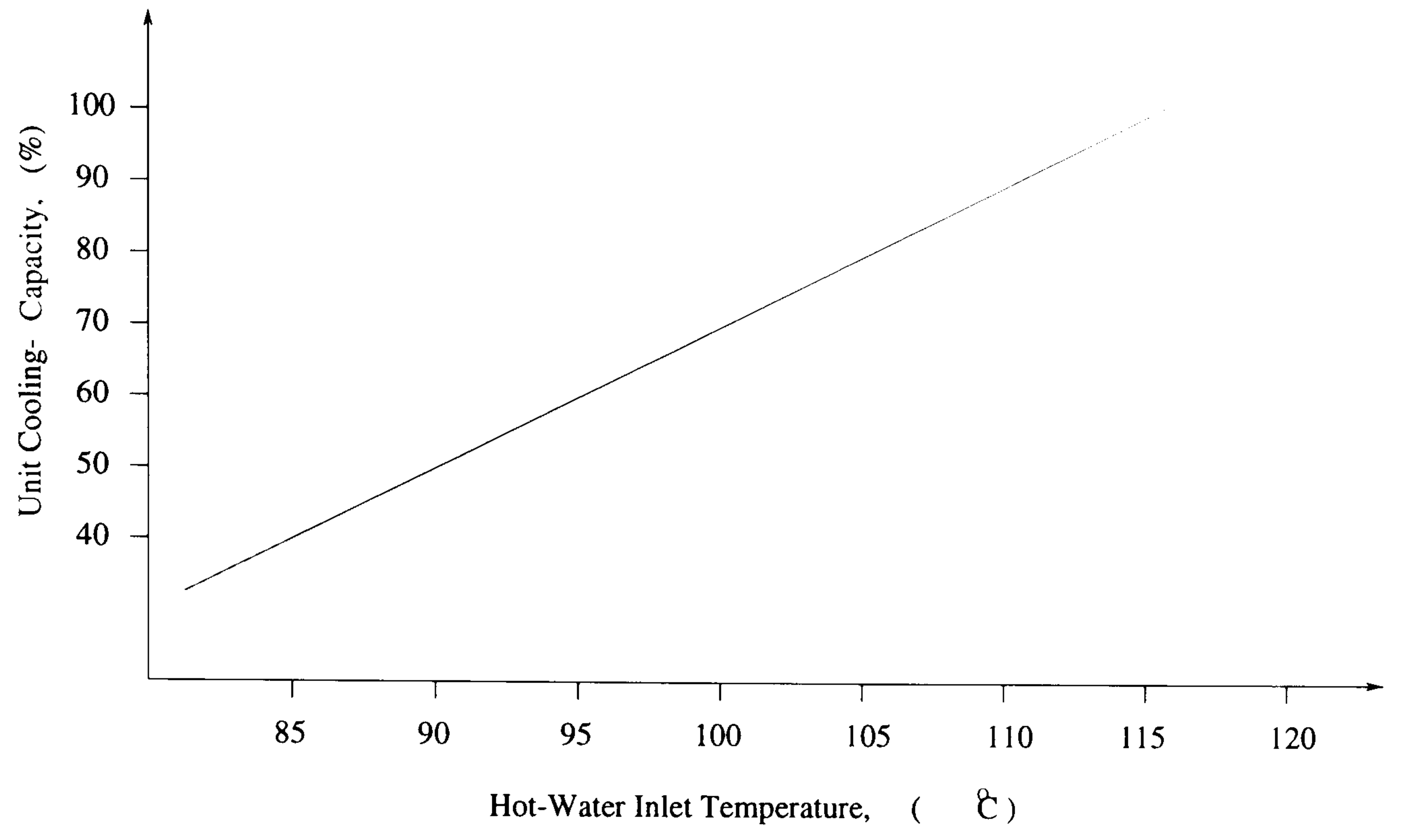


Figure 6.6: Variation of cooling capacity with hot-water's inlet-temperature [14].

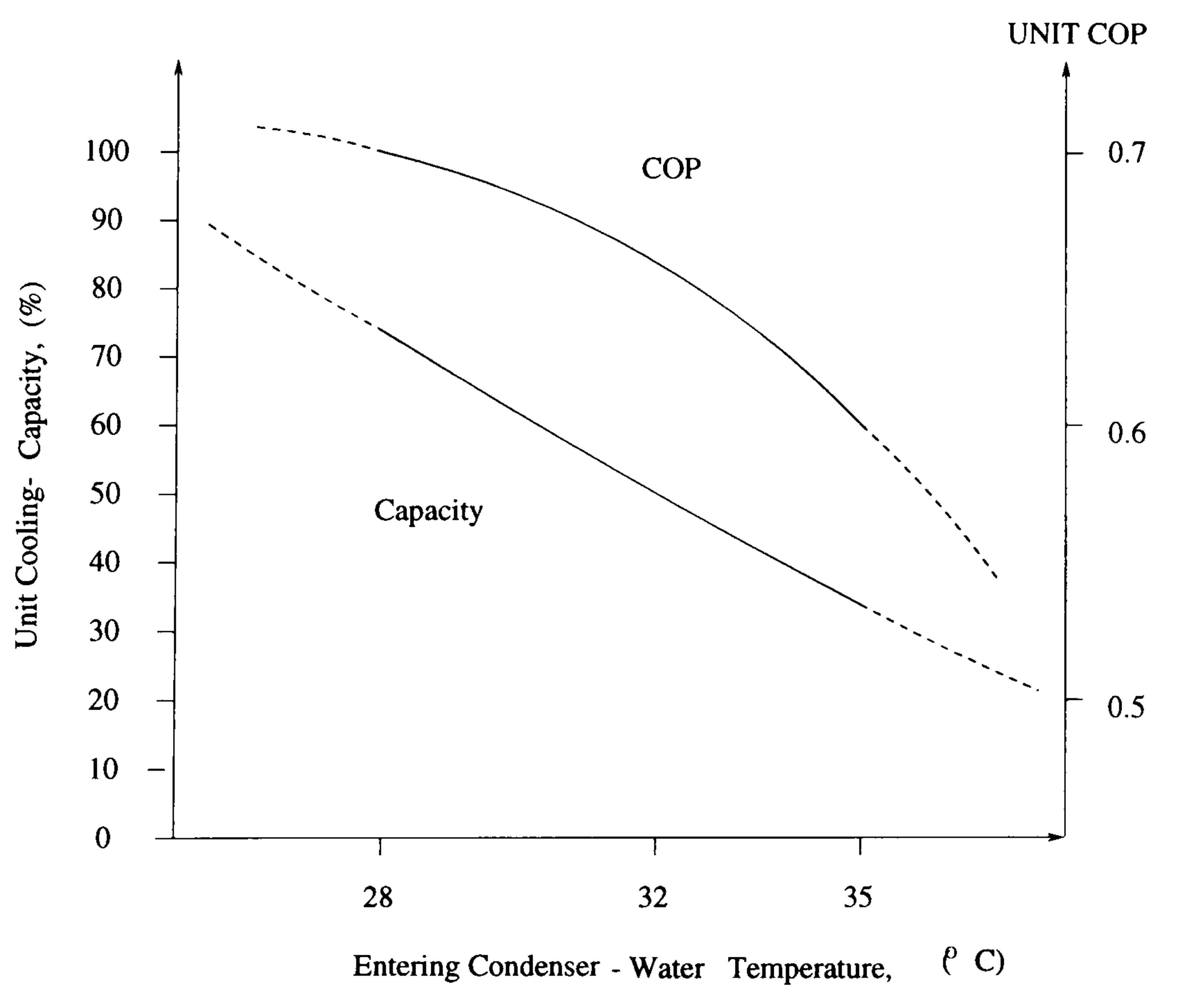


Figure 6.7: Variation of capacity and COP with condenser-water's temperature for a hot-water temperature of 100°C [14].

Relationships between absorber sections and external factors - It is possible to determine how the operation and performance of the absorber will change for varying conditions. The equations below give a simplified indication of some of the important relationships.

Generator Section

$$Q_g = Heat\ added\ to\ the\ generator \tag{6.4}$$
$$Q_g = \dot{m}_{CHP\ water} C_{p\ Water} (T_{CHP\ water\ in} - T_{CHP\ water\ out}) \tag{6.5}$$
$$Q_g = Heat\ of\ evaporation\ +\ Heat\ of\ solution \tag{6.6}$$
$$Q_g = \Delta s T_a \tag{6.7}$$

Condenser Section

$$Q_c = Heat\ extracted\ by\ the\ coolers \tag{6.8}$$
$$Q_c = \dot{m}_{Cooling\ water} C_{p\ Water} (T_{Cooling\ water\ out} - T_{Chilled\ water\ in}) \tag{6.9}$$
$$Q_c = \Delta s T_c \tag{6.10}$$

Evaporator Section

$$Q_e = Cooling\ effect \tag{6.11}$$
$$Q_e = \dot{m}_{Chilled\ water} C_{p\ Water} (T_{Chilled\ water\ in} - T_{Chilled\ water\ out}) \tag{6.12}$$
$$Q_e = \Delta s T_e \tag{6.13}$$

Absorber Section

$$Q_a = Heat\ of\ wetting \tag{6.14}$$
$$Q_a = r\ +\ l\ =\ \Delta s T_a \tag{6.15}$$

Operation of the absorption cycle for varying conditions -
(a) - Variation of the CHP unit's flow water temperature.
For single-stage absorption chillers, the relationship between source-water temperature and the temperature drop ΔT across the chiller can be approximated by the equation:

$$\Delta T = (T_{CHP\ IN}/4) - 15 \tag{6.16}$$

1. Q_g increasing will lead to an increase in the rate of evaporation of the refrigerant from the surface of the solution. This will also result in the rate of LiBr returned to the absorber increasing. Additionally, more heat will be passed from the LiBr being absorbent leaving the generator and given up to the solution entering the generator.

2. More vapour will be supplied to the condenser at a higher superheated temperature. The rate of sensible and latent heat given up to the cooling water will increase. This will lead to an increasing temperature of the cooling water coming from the cooling tower/air-blast coolers, or the rate of cooling from the tower can be increased thus maintaining the temperature of the cooling water returning to the condenser.

3. The rate of flow of the refrigerant passed to the evaporator will have increased, which in turn will accelerate the rate of evaporation of the refrigerant if the chilled water returns at a high enough temperature in order to boil off the refrigerant. If not, then the chilled water temperature will decrease, as will the efficiency of the chiller. If the required load does exist, then more refrigerant will be evaporated and passed on to the absorber when more water vapour will be absorbed by the increased concentration of solution as a result of more LiBr returning from the generator.

4. The overall effect will be to increase the cooling output from the chiller. However, the COP will not change significantly.

Heat-Rejection systems

There are two commonly-used methods for removing excess heat from absorption systems: wet cooling-tower systems and air-blast coolers. The latter are more expensive to buy than wet cooling-tower systems and will consume more electrical power for the fans during their operation. However, their main benefit is that they offer an alternative to the increased maintenance costs, which are required in wet systems in order to prevent the development of legionella forming in the evaporating water.
The cooling towers exist to remove heat from the refrigeration process. The cooling water is passed from the absorber and condenser to the cooling-tower by circulating pumps, where fans are used to remove the heat before the cooling-water is returned to the absorption system. Approximately 70% of the heat removed from the absorber is from the condenser. The temperature of the cooling water will

have a direct effect on the performance of the chiller. When a vapour-compression system is to be replaced with an absorption chiller, the cooling tower capacity will need to be increased. This is because absorption chillers require approximately 1.5 to 2 times more heat rejection from the system than similarly sized vapour-compression systems. The additional heat is generated as a direct result of the absorption process. As a result of increased heat rejection, the pumps and fans in the system will also need to be increased in power. For VC the pumping power required for the chilled water and cooling water systems will be approximately equal for simple pipe distribution systems. Longer pipe runs with more numerous bends will increase the pressure drop and result in the need for larger pumps. absorption chiller systems will, on average, require approximately twice as much pumping power to circulate the cooling water as the VC system [96].

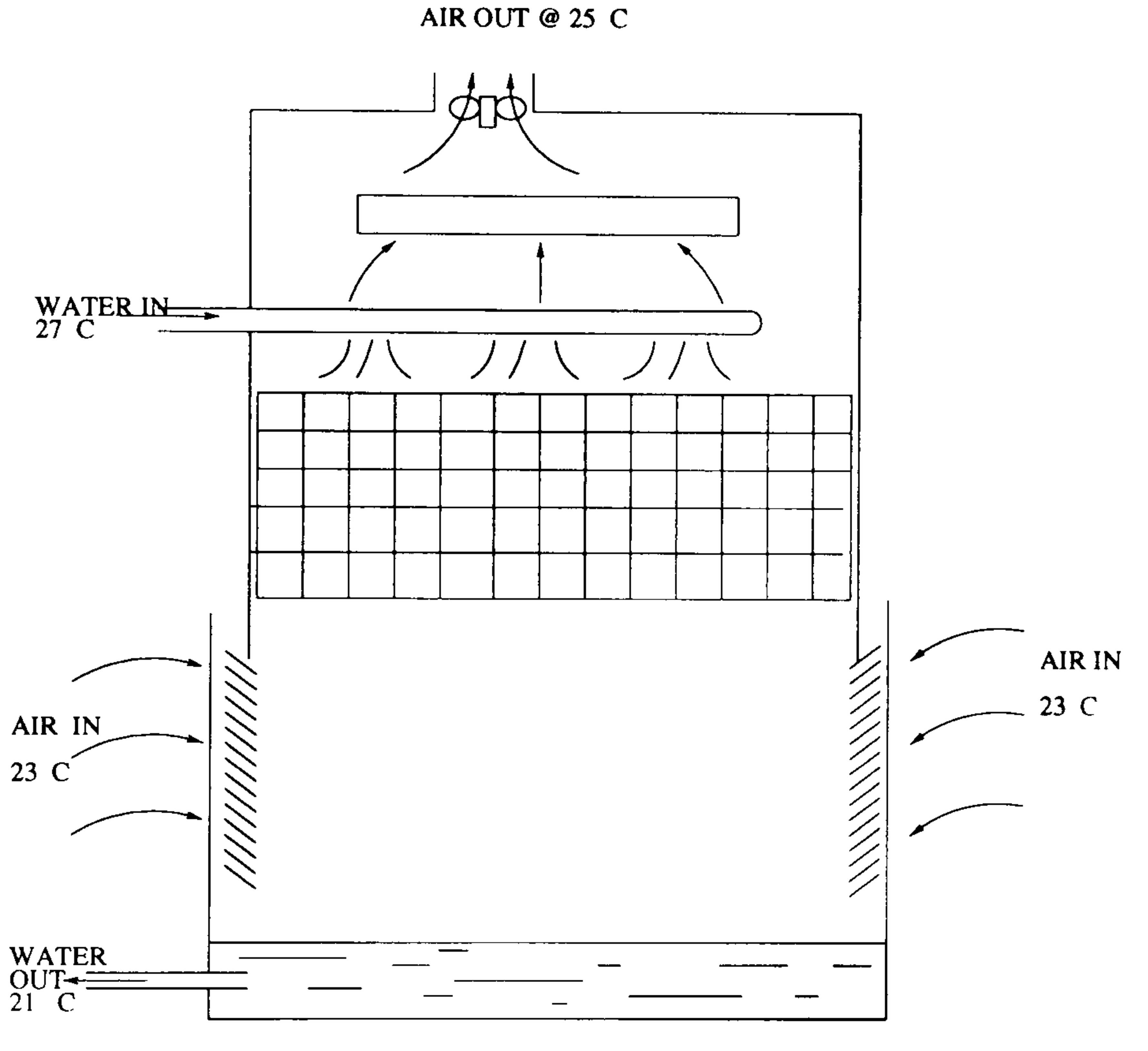


Figure 6.8: Cooling tower.

In typical absorption systems, the chiller is selected on the basis of the cooling-water temperature available at full load. This is the specified cooling-water inlet temperature. An alternative form of heat rejection is to pre-heat the boiler feed-water, which can help reduce the cost of heat rejection.

The chilled-water circuit

These pipe systems carry the chilled water, which is produced in the evaporator, to the point where space cooling is required. As with the cooling water system, the size of the pump will be dependent on the complexity and length of the pipe distribution system and the pressure drop across it.

Auxiliary components

The cooling water and refrigerant are circulated by electrical pumps. The size of the refrigerant pump required for an absorption system will be smaller and, therefore, cheaper to operate than the pump required for a similarly-sized compressor unit.

6.2.3 Maintenance of absorption systems

It is estimated that absorption systems cost approximately 0.6 to 1.25 times similarly maintained vapour-compression systems. The differential between the two types of systems has narrowed over recent years due to the introduction of direct digital controls (DDC) for absorption machines and the increased maintenance costs for vapour-compression systems resulting from the CFC-recovery requirements. Due to several factors, such as the corrosiveness of the solution and vacuum pressures, LiBr absorption machines have shorter life expectancies than vapour-compression machines. If properly maintained, a LiBr unit will last 70-85% as long as a comparable centrifugal machine [17]. Carrier single-effect absorption chillers in the 16JB range will require a major service once every six years [14].

Testing of the LiBr solution should be carried out at least once a year for single-effect systems and twice a year for double-effect systems. Testing should highlight any emerging problems which can then be rectified before significant loss of performance occurs.

Chemical additives - these are used in LiBr absorption chillers to reduce the potential for corrosion. They can also increase the mass/heat transfer achievable by the units.

Cryatalisation - is one ofthe most frequent causes of unscheduled downtime ans maintenance calls. Malfunctions in the air conditioning system controls, failure of a pressure reducing valve or electrical failure are the common causes. A positive concentration limit can avoid this problem by measuring the flow of the solution through the heat exchanger. When a restriction, which indicates impending crystalisation, is detected the chiller is switched off.

Primary corrosion-inhibitors used are lithium chloride (LiCrO_4), lithium molybade (LiM_oO_4) and lithium nitrate (LiNO_3).

Mass/heat transfers enhancement. The mass-flow of the refrigerant can be increased by up to 30% by the addition of C_8H_8 to the solution (1% of the LiBr solution by volume). This equates to a rise in machine output of approximately 10 to 20% [17].

6.2.4 The Cost of Cooling / Economies of Absorption Systems

The cost of cooling per kWh is greater than the cost of heating per kWh. Figure 6.9 illustrates how the cost of cooling for vapour-compression systems varies with the temperature required. As the required evaporator temperature decreases, the cost of cooling per kWh increases. The required cooling temperature is not the only factor to be concerned with when attempting to determine the cost of cooling.

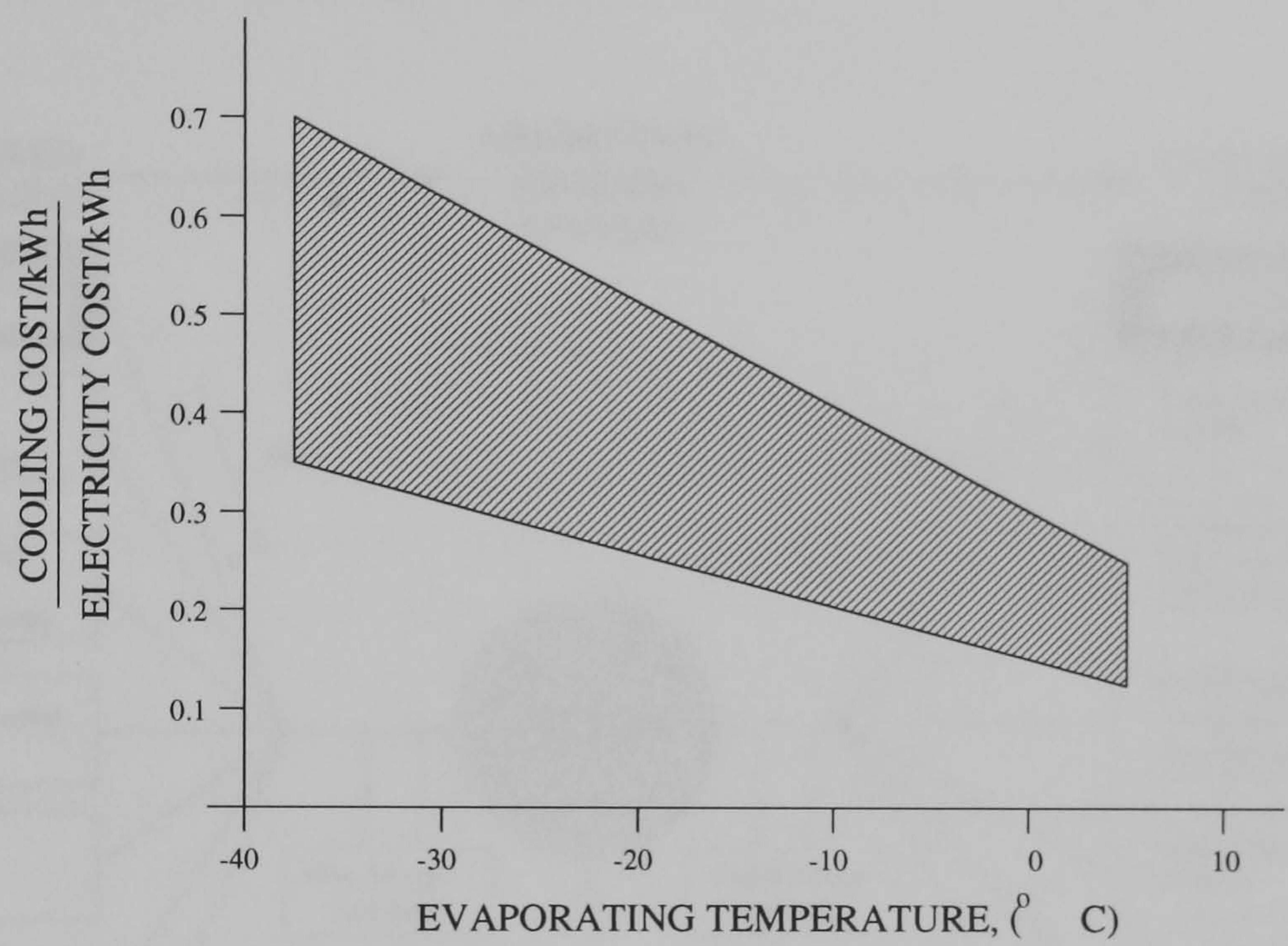


Figure 6.9: The cost of coolth [15].

Capital Costs

The capital costs of absorption chillers are greater than the cost of similarly sized compressor units. This is because of the relatively low numbers of absorption units which are currently manufactured compared with compressor systems, the unit-costs are high and are often more than twice as much as similarly-sized compressor systems. The COP of an absorption system will increase if a double-stage unit can be used. However, the additional performance obtained from a double-stage chiller comes at a price, as they can cost up to twice as much as single-stage chillers [43] and four times greater than VC systems. The 16JB range of absorption chillers produced by Carrier cost from £50,000 for the 16JB010 to about £126,000 for the 16JB068. These prices do not include the cost of the cooling tower or the installation of the system [97]. The capital cost of the chiller is a significant factor for the overall economics of the integrated CHP/absorption system. Current research, which is aimed at reducing the capital cost of the chillers has focused on the use of polymeric and metallic materials. These new materials have been partially tested and the results look promising for the further reduction of costs [98]. The installation of absorption systems can attract grants from various supporting agencies. The availability of such a grant would improve the perceived economics of a proposed system significantly.

6.2.5 Applications for Absorption Systems

In this study the main focus will be on the process of space cooling with the heat supplied from the CHP engine. Figure 6.10 summarises the other numerous applications for absorption chillers, and also gives a breakdown of some the various potential heat-sources. Air-conditioning (cooling) requires that the ambient air be cooled to between 12°C and 14°C in order to provide a comfortable working and living environment. This is conventionally achieved by circulating water at between 5°C and 7°C to the coils of a fan-blown air-handling unit and returning the water at around 12°C to the chiller.

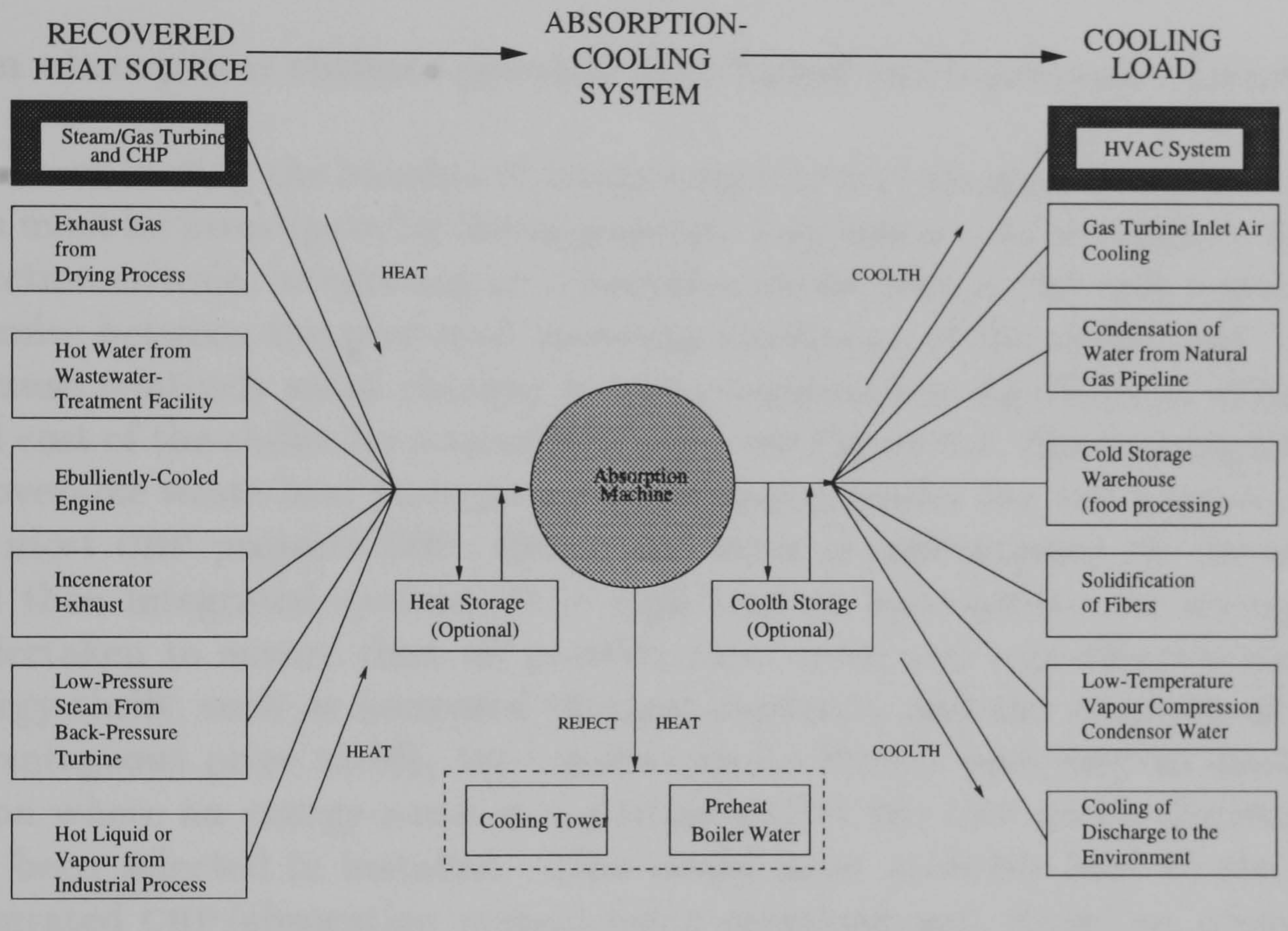


Figure 6.10: Absorption chiller applications.

Summary of the benefits of absorption systems.

- No CFCs employed, and so environmentally more friendly than conventional vapour-compression systems.
- One stage design for simple and reliable operation.
- Operates using low-pressure steam or hot water.
- Quiet and vibration free operation.
- Few moving parts and hence high reliability.

6.3 Integrating CHP and absorption chillers.

Chapter 3 of this thesis has already introduced the reader to CHP and presented some of the fundamental concepts which influences the viability of the integrated system now proposed. The scope for small-scale CHP will remain as defined earlier (i.e. $15kW_e$ to $1MW_e$).

The previous section of this chapter introduced some of the background to cooling technology and in particular to absorption cooling.
This section will now address the specific technical and operational tasks which must be considered and evaluated in order to test the hypothesis 3:

Can absorption chillers provide significant environmental benefits.

When evaluating the benefits of integrating CHP and absorption chillers, many factors must be investigated if the appropriate conclusion is to be reached. In terms of selection criteria, integrating an absorption chiller with a CHP unit requires a compromise between the preferred operating conditions of the chiller and the engine, because relatively small changes in water temperature significantly affect the size and cost of the chiller for a specified duty - see Figure 6.6. Maximising the value of recoverable waste-heat from power generation provides the real economic impetus for most CHP projects [99]. Before the focus is concentrated on the individual, and then integrated systems, it is vital that an appropriate site energy-audit is undertaken to ensure than all possible short-term and cost-effective measures of energy-thrift, such as increased thermal insulation and the adoption of the most advantageous price tariffs, are implemented. This is necessary to avoid the position where an energy-audit is undertaken after the CHP unit's electrical output has been selected in installed. This would most probably lead to the proposed integrated CHP/absorption system being oversized and, therefore, uneconomical. For this study, it is assumed that the site energy demand profiles will have already been adjusted following a full energy audit.

In order that this investigation is carried out as fully as possible, it is important to: -

i) undertake a full energy audit of the proposed site (assumed to have been undertaken).
ii) obtain the electricity demand profiles for the site.
iii) determine the heat demand from the building for hot water and space heating.
iv) describe which type and size of CHP unit to be installed.
v) the recoverable heat from the CHP unit, both before and after the other heating demands at the site have been satisfied.

vi) the cooling or refrigeration requirements and design conditions at the site.
vii) document the existing cooling system, if any.
viii) choose the type of absorption chiller to be installed at the site.
ix) determine the size of absorption chiller to be installed at the site.
x) predict the cooling output attainable from the absorption chiller.
xi) calculate the heat rejection requirements of the absorption chiller.
xii) determine the electric power requirements of the system.
xiii) assess the part-load performance of the CHP unit and the absorption chiller.
xiv) decide any specific heat-transfer requirements.
xv) settle upon the most effective operating configuration for the integrated system.

Some of these points will be site specific and, therefore, their determination will be undertake together with the site study.

(i) Site energy audit. Assumed to have already been undertaken.

(ii) The electricity-demand profiles: These will be presented in kW_e and kW_T for each hour of the day. A set of hourly demands will be obtained for one day in every month of the year. These demand profiles are site specific.

(iii) The heat-demand profiles for hot water and space heating: As (ii) and the profiles will be site specific.

(iv) The type and size of CHP unit to be used: Only small-scale reciprocating engines (between $15kW_e$ and $1MW_e$) will be considered for this study.

(v) The recoverable heat from the CHP unit.
This will be determined for the cases with and with a heat demand for water and space heating from the site.
(vi) The cooling requirements and design conditions at the site: This will be a function of the size and location of the buildings and rooms, the geographical location of the building, the number of people resident within the building, the amount of heat-emitting equipment in the rooms, the quality of insulation/construction of the building and the required temperature settings. These will be site specific. The design conditions will include:

- leaving-chilled-fluid temperature (^oC);
- chilled-fluid temperature rise, difference at process (^oC): this determines the chilled-water temperature entering the absorption machine;
- entry-cooling-water temperature (^oC);
- cooling water temperature rise in the absorption unit (^oC);
- ambient wet-bulb temperature (^oC);

(vii) Document the existing cooling system: The economics of the proposed new system may be enhanced if, for example, the existing air-conditioning units had become obsolete or too expensive to maintain and operate. Therefore, it may need to be replaced in any case. Consequently, part of the capital cost of the new absorption chiller could be offset by not replacing the existing air-conditioning system with like-for-like equipment. It is also important to discover if any of the existing AC equipment can be reused or modified in any way so as to reduce the capital costs of the new system. Consider also the case where some form of top-up or back-up cooling ability is maintained (i.e. the cost of operation and reliability).

(viii) The type of absorption chiller: This will be dependent on the type of CHP unit employed and the cooling temperatures required at the site. Small-scale reciprocating CHP units will usually produce hot-water in the temperature range 90 to 105°C. The considered requirement for chilling is for space cooling. Consequently, a single-stage LiBr absorption chiller will be the most appropriate unit because it can operate with a relatively low source stream temperature and it produces chilled water at 4°C to 7°C.

(ix) The size of the absorption chiller: This is partially site specific and partially dependent on the quantity of heat available from the CHP unit.

(x) The cooling output attainable from the absorption chiller. This will require a detailed study of the absorption chillers likely operating conditions.

(xi) Heat-rejection requirements: A decision is requires as to whether to select cooling towers, air-blast coolers or some sort of boiler feed pre-heating.

(xii) Electric power requirements of the system: The absorption chiller system will require additional pumping power to remove the extra heat generated in the absorber.

(xiii) The part-load performance of the CHP unit and the absorption chiller: This information is provided by the manufacturer's specifications.

(xiv) Any specific heat transfer requirements: Does the system need to be protected from fouling or are there any specific heat-transfer characteristics?

(xv) Most effective operating configuration for the integrated system: This will usually require that the absorption chiller operates as the lead chiller and the CHP as the lead boiler. However, on occasions cooling requirements may be a priority, consequently the heating requirements can be satisfied by the back-up boiler or vice versa.

6.3.1 Matching Heat Sources, Cooling Loads and Heat Sinks.

The following points of the proposed system should be examined in detail:

1. The heat source
2. The cooling load
3. The heat-exchange mechanism
4. The heat sink

Heat Source
The appraisal must begin by considering the mass-flow rate, the temperature and intermittency of the heat stream produced by the CHP unit.

Temperature - The source heat stream temperature will determine the type of absorption chiller to be used in the integrated system (see Table in 1 in chapter 3). The temperature of the heat stream produced by a CHP unit will be dependent on the type (i.e. reciprocating engine, gas turbine, steam turbine etc.) and the size of the unit employed (i.e. $15kW_e$ up to $1MW_e$ for this investigation). The small-scale reciprocating engines will produce hot water at between 80 and 110^oC. The temperature of the heat utilised by the absorption chiller will be a function of the heat-source-stream temperature and the heat-exchange mechanism used. Heat exchangers will usually be required to avoid the contamination or corrosion of the absorption system by the heat-source.

Fluid flow-rate - When a CHP unit is operating at constant electrical load - which it will usually have been sized to do - it will also be producing a constant heat output. Therefore, it would, under these conditions, be suitable to operate in conjunction with an indirectly-fired absorption chiller, which require a steady flow of recovered heat at constant temperature in order to produce a constant cooling output. However, CHP units have usually been sized so as to satisfy as much of the winter heat demand as possible, together with all of the summer demand for heat according to site energy-demand profiles. Consequently, CHP heat output will not be available for the absorption chiller in winter and will probably only be so intermittently during the summer. As a result, supplemental boilers may be required to maintain the cooling output, or the system may prove impractical. The determination of the correct sizing of the CHP unit and absorption chiller will only be achieved through a detailed analysis of the site's energy-demand profiles and the operating conditions of all of the individual systems. For this, it is necessary to develop a predictive model which can undertake easily a sensitivity analysis of the proposed system.

The cooling load. The cooling-demand profile will be one of the main factors which will dictate the system's operating configuration.

The heat sink. The absorption system will require a heat sink. This is usually achieved via a cooling tower or air-blast coolers. However, other options, such as boiler feed-water pre-heating can be used.

Figure 6.11 illustrates the various inputs and outputs to, and from, an absorption chiller. Variations in fluid flow rates ($\dot{m}$) and temperatures (T) will result in different levels of output from the absorption chiller.

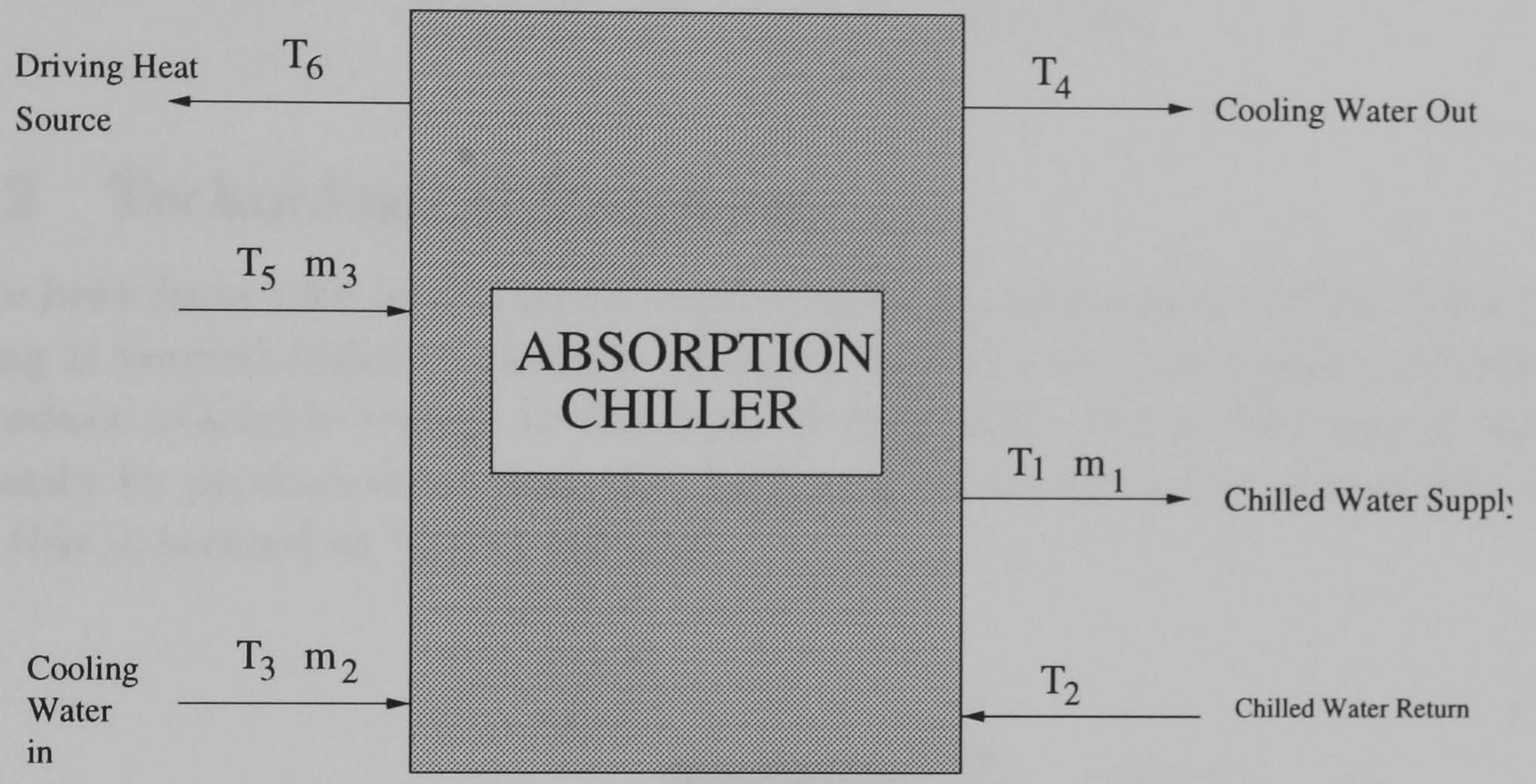


Figure 6.11: Absorption chiller input/output.

- If the heat input (specified by $\dot{m}_3, T_5 \ to \ T_6$) is decreased, then the cooling output flow ($\dot{m}_1, T_1 \ to \ T_2$) decreases.

If the quantity of heat is known, then the amount of heat can be estimated using the following equation:

$$q_{cooling} = COP_{ABS} \frac{q_{recovered}}{C_1} \tag{6.17}$$

where

$q_{cooling}$	=	cooling output, kW_T
COP_{ABS}	=	coefficient of performance of the absorption machine.
$q_{recovered}$	=	heat recovered from jacket/exhaust gas, kW_T
C_1	=	constant, 1 $kW_{T,Heat}/kW_{T,Coolth}$

	Single-Effect LiBr Machine	Double-Effect LiBr Machine	Low-Temperature Ammonia Machine
Steam input, (kPa)	135-205	110-120	100-1480
Steam input, ^oC	110-120	175-185	100-195
Hot Water input, ^oC	115-130	155-205	100-195
Cooling Output, ^oC	4-16	4-16	-51-4
COP	0.6-0.7	0.9-1.14	0.1-0.8

Table 6.1: Absorption chiller data.

6.3.2 Technological Problems.

Waste heat from CHP units can be used to drive an absorption chiller. This type of cooling is termed indirect chilling because the fuel source is being used primarily to produce available energy in the form of electricity. If the fuel source was used primarily to produce heat and this heat is used to drive the absorption chiller, then this is termed as 'direct chilling'.

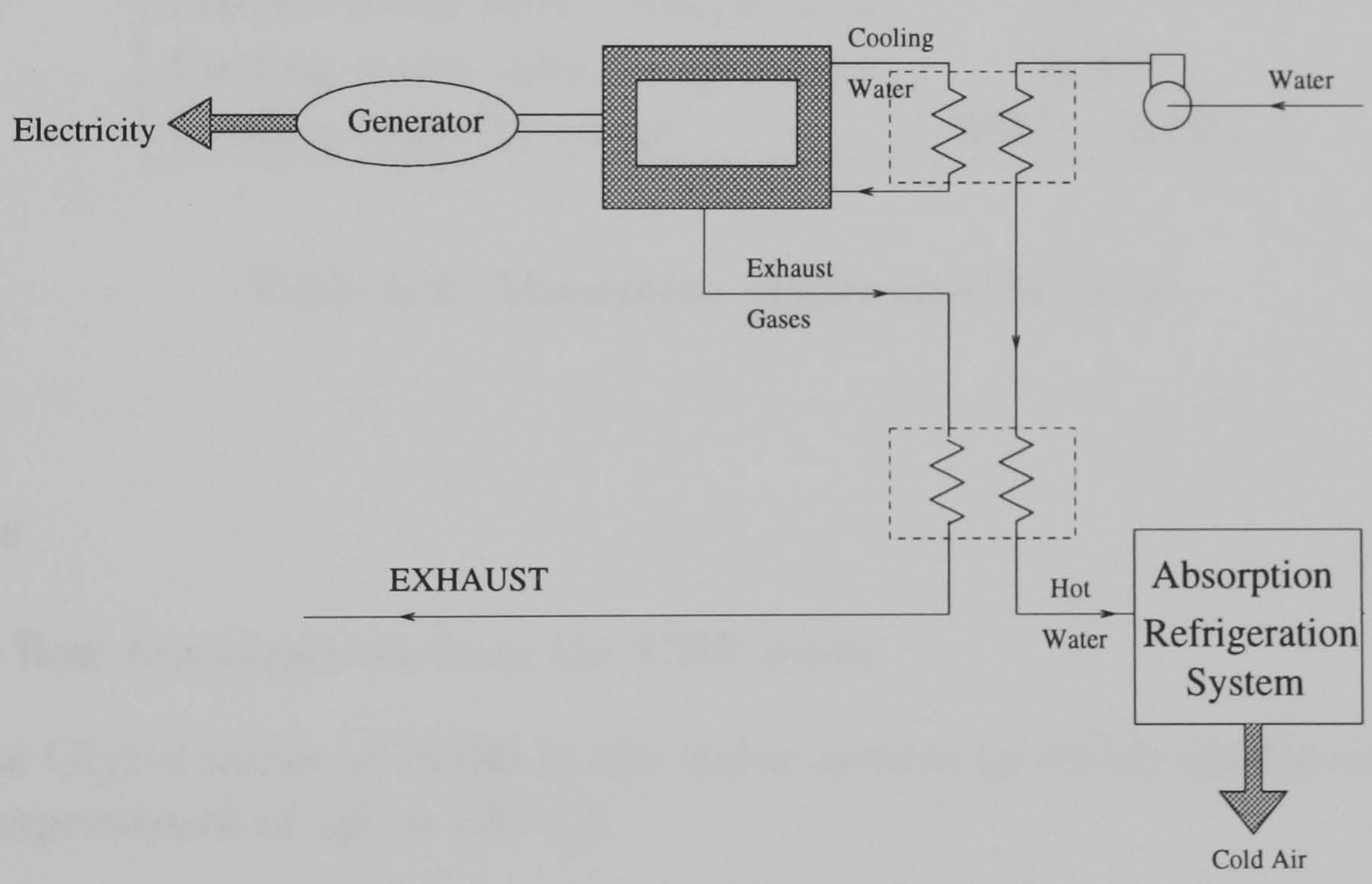


Figure 6.12: Integrated CHP/absorption cooling system [16].

Small-scale CHP units will produce hot-water at about 90^oC which is the lowest temperature at which hot-water fired absorption chillers can operate efficiently. Therefore, an objective of this research is to determine if, and how, both the CHP units and the absorption chillers can be modified in order to improve the viability of the proposed combined systems.

6.3.3 CHP hot-water for absorption chillers.

Figure 6.12 indicate how CHP units and absorption chillers can be connected for operation. The main drawbacks for absorption systems are their relatively low COPs (i.e. 0.6 to 0.7) and their relatively high capital and installation costs. These can be partially offset by the benefits produced through the demand for low-grade heat from the chillers.
Most small-scale CHP units produce a maximum hot-water temperature of between 90 and 95°C (5kP to 70kP steam pressure). Increasing temperatures above this point will give rise to operation and combustion difficulties. There is also a practical operational range for the temperature of the lubricating oil circuit (namely 90 to 100°C) with 120°C being the absolute maximum.

Hot-Water fired absorption chillers - These are the most suitable types of absorption systems for small-scale CHP as the heat input is in the form of hot-water at between 85 and 90°C. Table 6.2 gives some operational characteristics of a small-scale absorption chiller.

Hot-water absorption chiller characteristics	
Supply hot water temperature	90°C
Hot water flow rate	$0.883 m^3/h.RT$
Chilled-water outlet temperature	8°C
Cooling-water inlet temperature	29.4°C
Cooling capacity range	30RT - 525RT

Table 6.2: Absorption chiller specifications.

Options

Increase flow temperatures from the CHP units.

1. Use Glycol mixes of 70/30 in the water system (possibly giving engine jacket temperatures of up to 135°C).
2. Reduce the hot-water mass-flow rate through the engine (so collecting less thermal-energy in total, but at a higher temperature).
3. Pressurise the hot-water system and run the engine at higher temperatures.
4. Extract heat separately from the exhaust gases.

Disadvantages of increased temperatures.

1. Damage to the seals and gaskets.
2. Machine tolerances.
3. Cooling-passage fouling from impurities in the top-up water added.
4. The ability of the lubricants to continue to work satisfactorily for an economical length of time.

Attempts have been made to increase the heat-output efficiency from the CHP units through the maximised thermal insulation of the pipes etc., and by adopting more effective heat-exchangers, all of which lead to an additional 5% heat-output efficiency. However, such additions can lead to a more than 100% increase in the total capital and installation costs for the unit.

6.3.4 Application of absorption chillers to small-scale CHP systems

When locating a potential heat-source, it is necessary to evaluate several characteristics. The following variables are used to determine if the heat source is adequate:

- temperature of the heat-stream source.
- flow rate of the recovered heat-stream.
- chemical composition of the source heat-stream.
- intermittency of the recovered heat-stream temperature and flow-rate.

Part-load performance of the absorption chiller

Throughout the year, the demand for cooling will vary considerably. This will require that the operation of the integrated system is managed correctly. If the system has a mismatched load, then the base cooling-load should first be supplied by the absorption chiller, and further cooling requirements met by the VC systems. As the demand for cooling decreases below the capacity of the absorption chiller, the amount of heat supplied to the generator decreases and reduces the solution temperature. By decreasing the solution temperature, while maintaining the chilled-fluid outlet temperature, the solution becomes more dilute (i.e. more refrigerant stays in the solution and less refrigerant flows through the system). Therefore, part-load performance means that the absorption process shrinks to the left on the PTX chart.

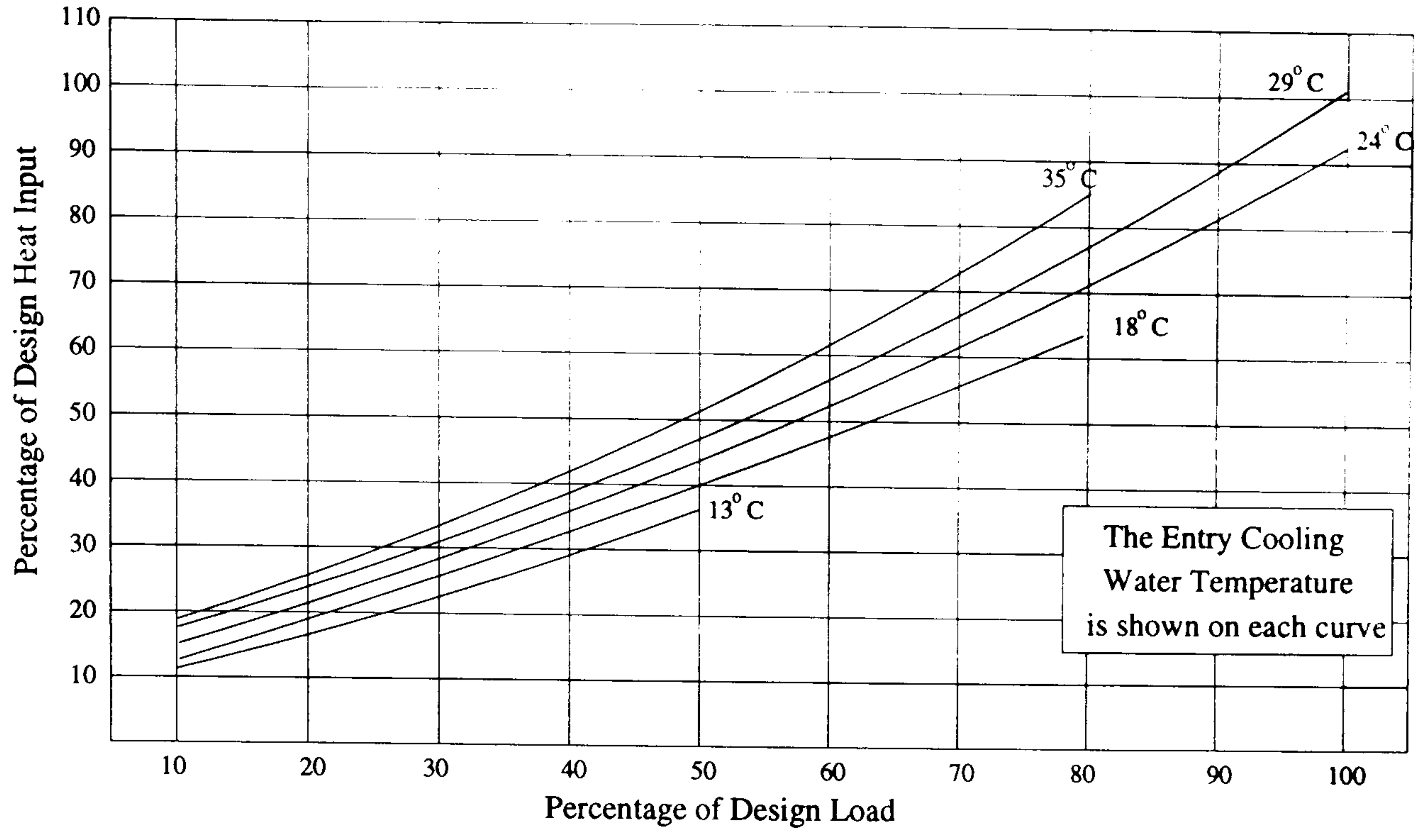


Figure 6.13: Part-load capacity chart for a single-effect LiBr absorption chiller [17].

6.4 Development and application of the predictive model

If a CHP unit is to be installed together with an absorption chiller, then the potential heat available from the CHP unit after it has satisfied the sites other heat demands must be determined and synchronised with the demand from the chiller. For MKGH a computer program has been developed to determine when and how much heat will be available for each month of the year so that the economic viability of the proposed system can be determined.

As with the two previous systems proposed in this thesis, because of the complexity and multitude of calculations required, it is necessary to develop a predictive model to test the hypothesis. The computer model is required to produce test simulations of how CHP units and absorption chillers would operate with respect to the matching up of the; demand for electricity and heat from the site, the waste heat from the CHP unit, the demand for heat from the chiller and the demand for cooling from the site. Initially the simplest form of the model was developed and tested before being extended to account for an increasing number of variables, so as to represent a more realistic system. The computer program is has been written in Fortran 77.

6.4.1 Application of the model to a case study

Two CHP units have already been installed successfully at the Milton Keynes hospital in phases 1 and 2, and so a lack of awareness or distrust of this technology, or an absence of exemplars, are not barriers to further CHP investments.

Running the absorption chiller should boost the hospital's overall heat-demand during the summer and so reduce the 'summer dip' in the heat-demand profile (see Figure 6.14). The least rate of heat-demand is usually the greatest constraint on the size of the CHP unit to be installed. Additionally, the absorption chiller will displace the electricity consumed by the air-conditioning units, consequently, reducing the hospital's overall demand for electricity. The hospital's existing cooling-demand can thus be transformed into the chillers heat-demand, which will contribute to the hospital's overall heat-demand during the cooling (summer) months.

A small-scale packaged CHP unit would appear to be suitable for phase 3 of the hospital. An appropriate chiller would have input requirements that can be satisfied by such a CHP unit. Sayno are the only manufacturers providing a unit in the UK of adequate size for this purpose. The CHP unit's output is well-matched with the chillers demand-input and a site survey revealed that there was sufficient room within the existing plant room to accommodate both machines. Also integrating the two should be mechanically straightforward.

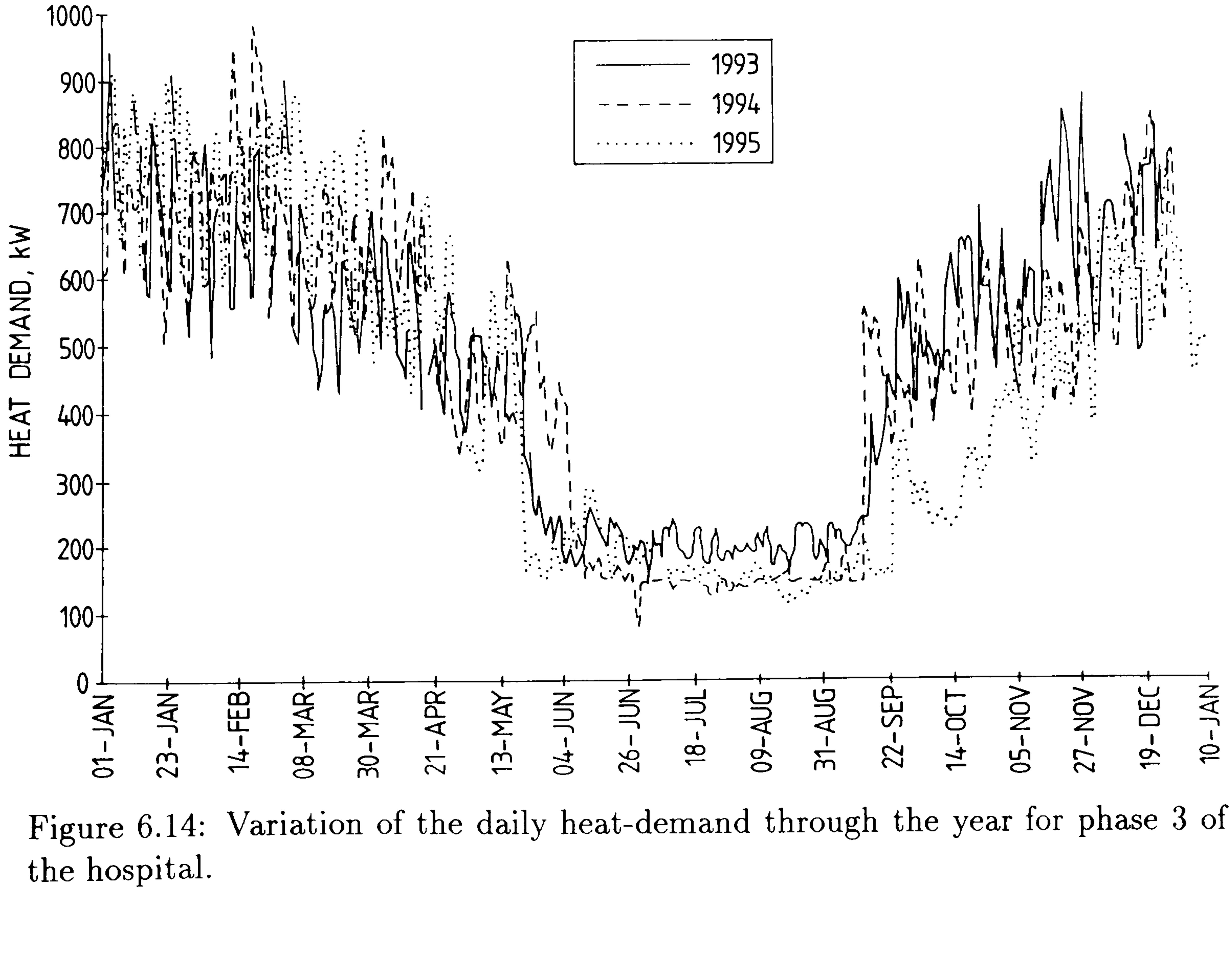


Figure 6.14: Variation of the daily heat-demand through the year for phase 3 of the hospital.

6.4.2 The feasibility study

Besides assessing the feasibility and desirability of installing the system in engineering (and especially energy) terms, the primary aim is to determine its commercial feasibility. As such, a financial approach is taken, so that the client can decide as a result of the study whether to invest more resources to install a CHP unit with, or without, an absorption chiller.

Care is taken to employ only actual data for all the commercially-available CHP units to be used on site. As a result, comprehensive information was obtained from the manufacturers, viz. full technical specifications, part-load performance and capital costs. Such detailed data are needed as input to the hourly-simulation program used to predict the optimal system for the required duty.

Most major manufacturers have simulation programs for system sizing. Their widespread use enables improved assessments to be obtained at the feasibility-study stage. The program (see later) used in this investigation is crucial to undertaking the sensitivity analyses for different CHP unit sizes to determine the optimal system.

For this macroscopic feasibility study, a detailed design of the proposed system is not undertaken, e.g. for the chilled-water pipe runs, the link between the chiller and the CHP unit, and for the connection of the CHP to the existing hot-water system. Instead budgeted cost-figures are obtained from manufacturers and expert consultants for the economic analysis.

The hourly-simulation program

Simulation programs are popular and reliable tools nowadays for predicting the performance of many systems. The hourly-simulation program follows the procedure shown in Figure 6.15 [100] and requires the following inputs:

- hourly heating , cooling and electrical demands
- part-load performances of the CHP units and the chiller
- costs of electricity and gas unit rates

The optimal size of a CHP unit depends more on the demand profiles for heat and electricity over a day, and a year, than on average demands. This is because the system's viability depends on maximising the running hours. The demand profiles for heating, cooling and electricity must be superimposed in order to determine whether the demand patterns coincide, and which will dictate to the optimal size of CHP unit for a specific purpose.

The Building's Energy-Management System (BEMS) at the hospital is useful for providing these data in addition to its key role for integrating the energy-management procedures for the whole site. Daily natural-gas consumptions are obtained and used to give the profiles shown in Figure 6.17. Profiles for electricity demand and for heat demand, incorporating the absorption chiller load, are shown in Figures 6.16 and 6.18 respectively.

A Hawk meter, an instrument that monitors all the parameters of 3-phase power, generated the profiles presented in figure 6.16. The meter monitored the electrical consumption for phase 3 throughout 28 days (referred to as 'multi-day' monitoring) from which it produced average consumption-profiles for each day of the week. The profiles from the meter show the electrical consumption for each electrical phase ('circuit'), and also stacks them to give the total rate of consumption. The meter also records the power factor (PF).

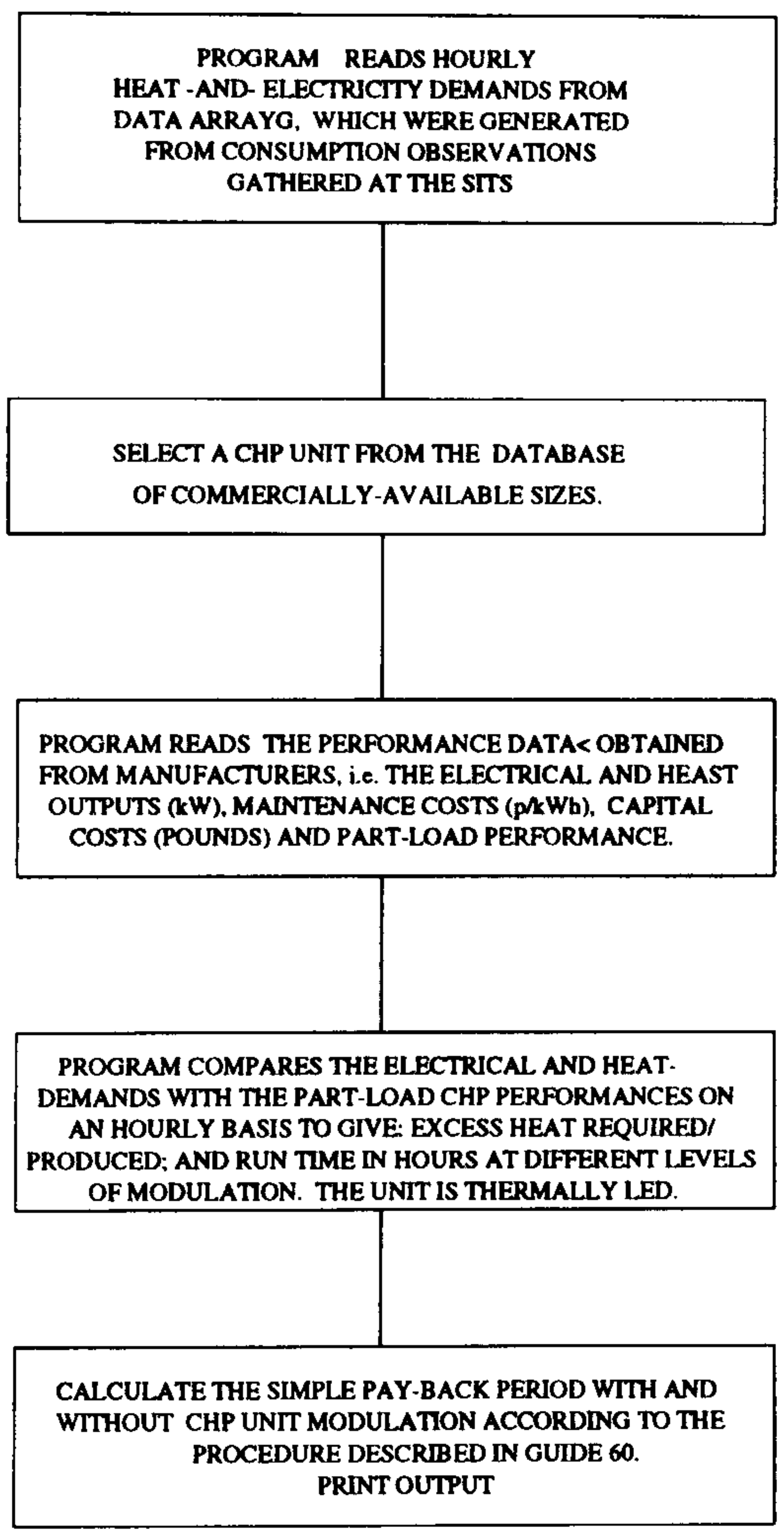


Figure 6.15: Flowchart for computer program.

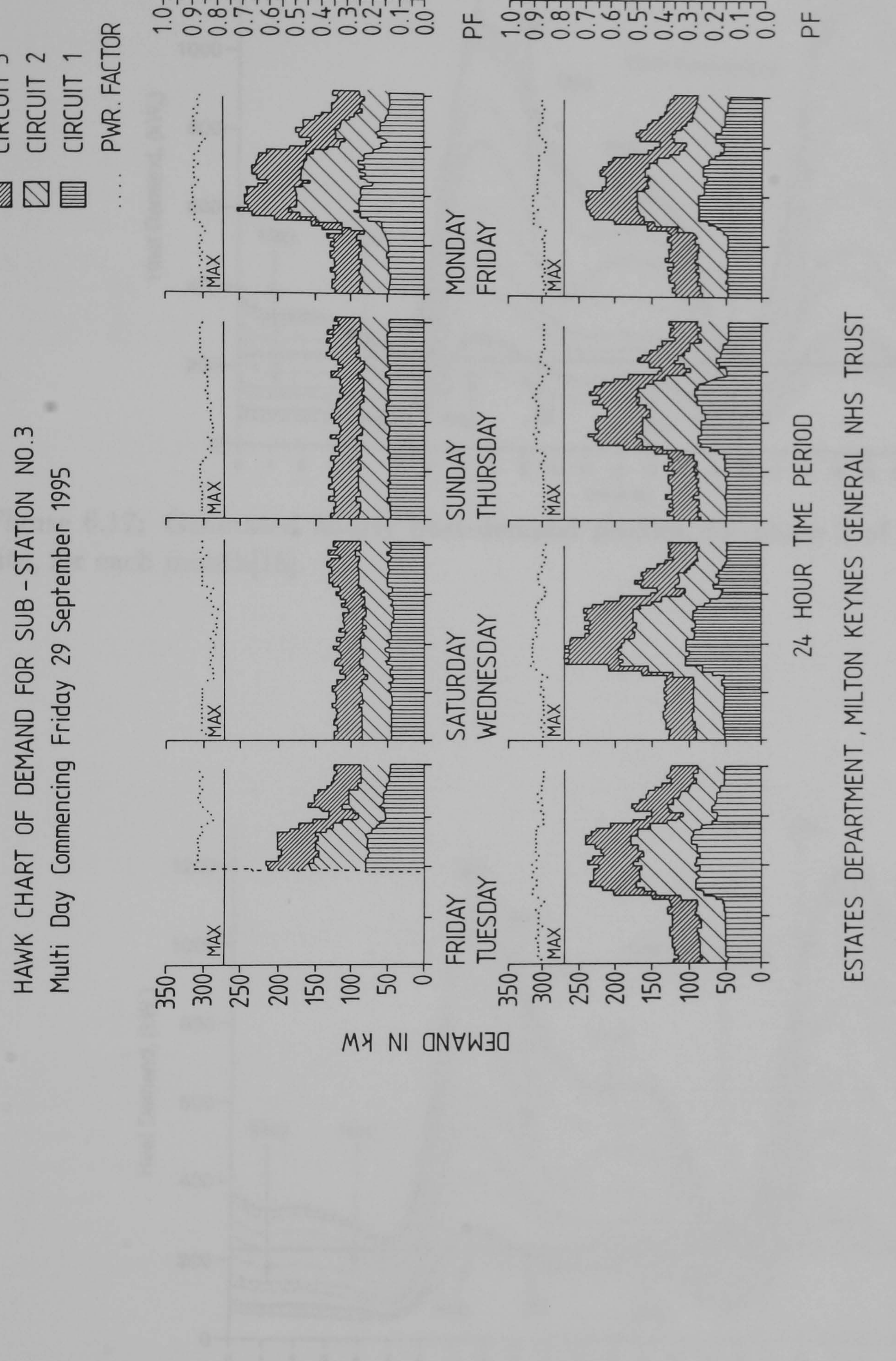


Figure 6.16: Electrical-demand profiles for each day of the week[18].

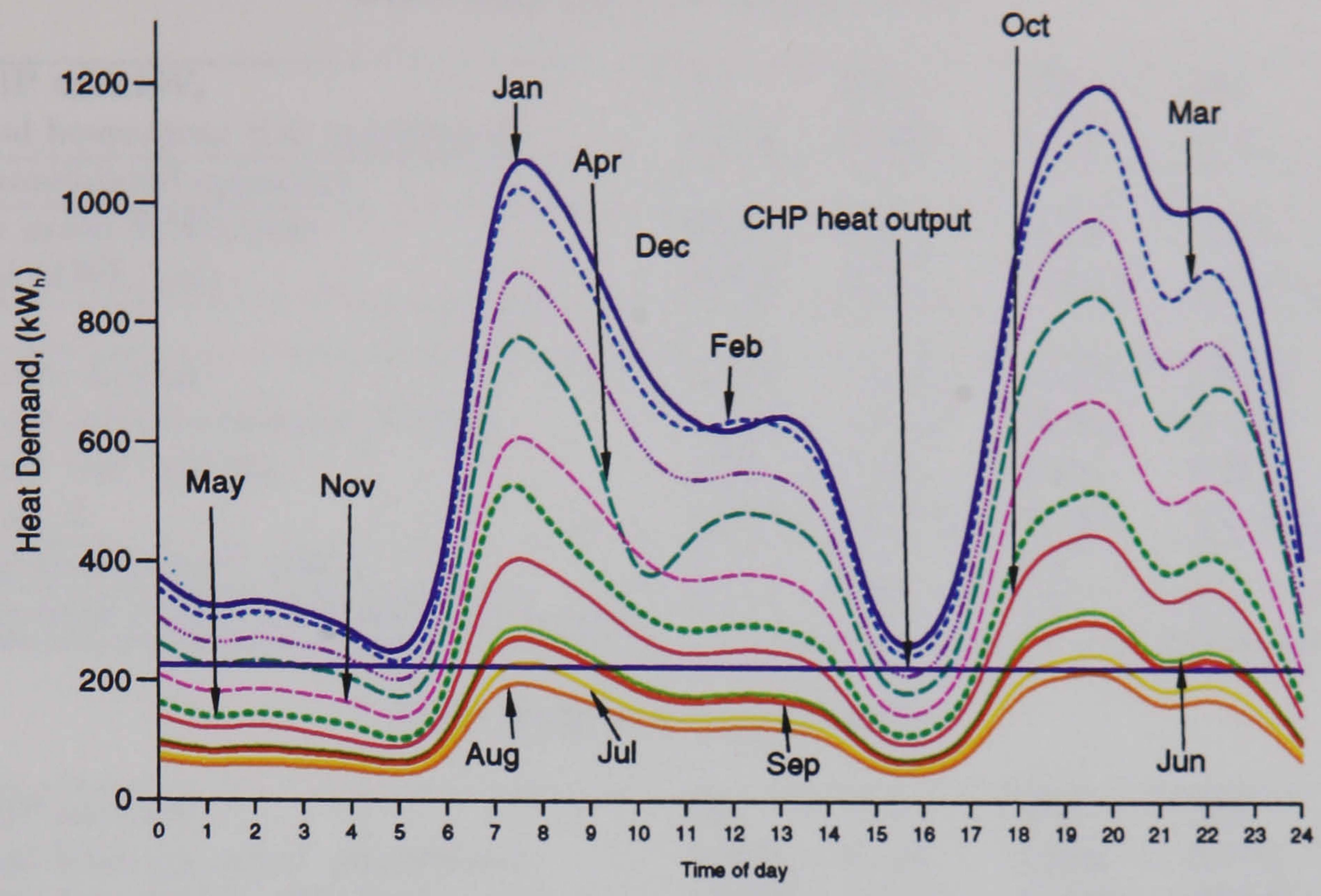


Figure 6.17: Generated hourly heat-demand profiles, for phase 3 of the hospital site, for each month[18].

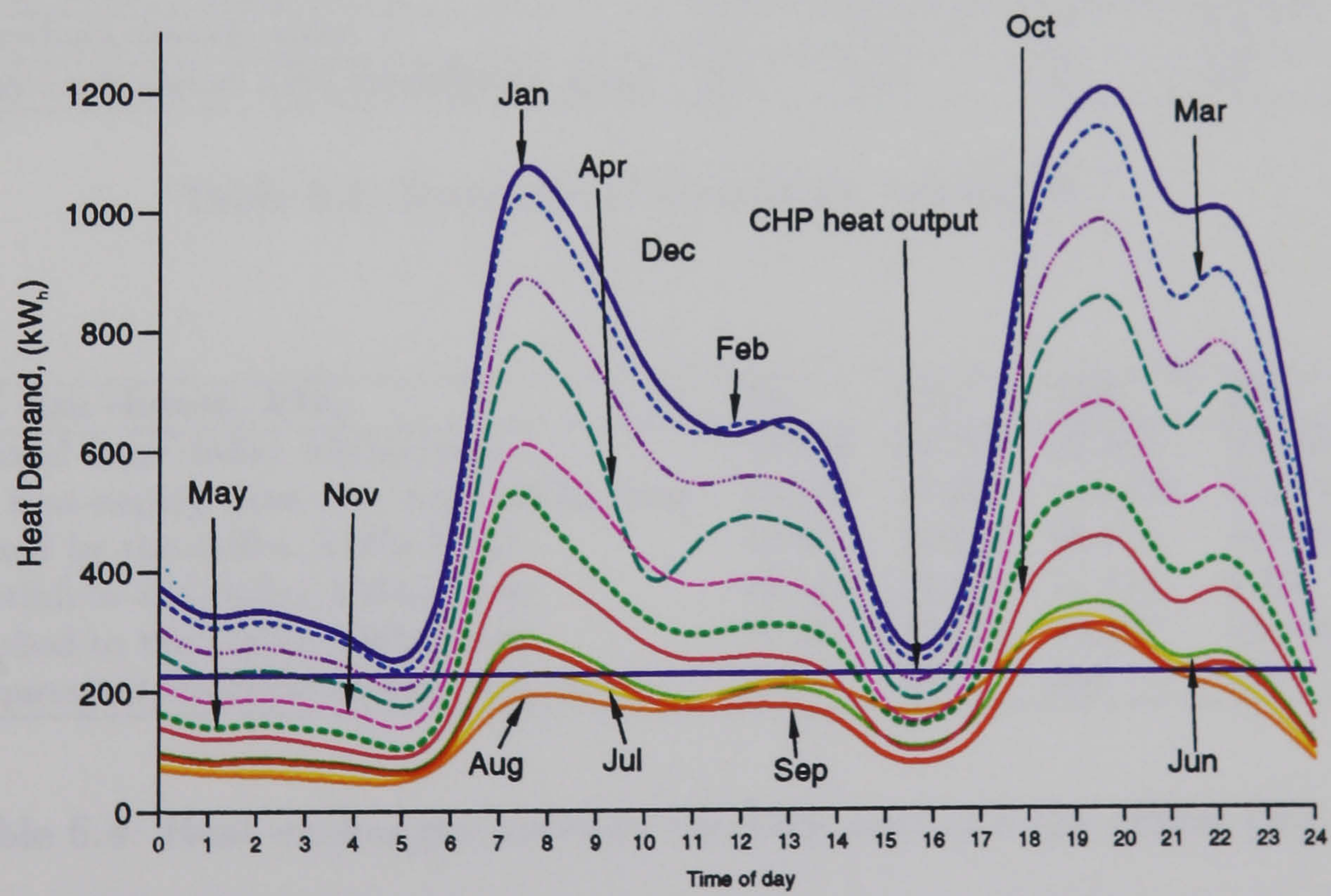


Figure 6.18: Generated hourly heat-demand profiles, for phase 3, including those for absorption cooling[18].

CHP **without** absorption chiller					
Size of CHP unit,kW_e	70	110	150	200	220
Operational hours/year (i.e. modulated)	6,112	5,889	5,777	5,190	5,038
Savings - modulated operation					
Electricity saved MWh/year	421.6	630.0	811.8	771.5	775.0
Heat saved MWh/year	686.5	979.3	1,223.1	1,505.0	1,539.0
Costs					
Running cost, £/year	7,411	11,857	15,118	19,831	23,714
Running cost with modulation, £/year	7,214	11,016	13,365	15,190	17,562
Maintenance cost, £/year	3,679	5,191	7,366	7,266	9,421
Capital cost, £	42,000	61,250	74,500	100,000	98,500
Simple pay-back period, years	3.3	3.4	3.3	5.4	7.4
Simple pay-back period with modulation, years	3.2	3.1	2.9	3.7	4.0
CHP with absorption chiller					
Size of CHP unit,kW_e	70	110	150	200	220
Operational hours/year (i.e. modulated)	6,205	6,175	6,054	5,717	5,533
Heat supplied to chiller, kWh/year	10,889	30,813	46,887	56,948	57,830
Savings - modulated operation					
Electricity saved MWh/year	432.6	667	862	845	850
Heat saved, MWh/year	693.8	1,007	1,252	1.573	1,601
Value of 'electrical' cooling saved, £/year	70	197	302	367	373
Costs					
Running cost, £/year	7,410	11,857	15,118	19,831	23,714
Running cost with modulation, £/year	7,388	11,636	14,165	16,500	18,993
Maintenance cost, £/year	3,735	5,434	7,719	8,004	10,347
Capital cost (CHP+Chiller), £	82,000	101,250	114,500	140,000	138,500
Simple pay-back period, years	6.2	5.1	4.6	6.4	8.4
Simple pay-back period with modulation, years	6.2	5.0	4.3	5.0	5.5

Table 6.3: Summary of simulation results[18].

CHP **unit size chosen, kW$_e$**	**70**	**110**	**150**	**200**	**220**
Heat-demand from chiller, kWh$_T$/year	59,303	59,303	59,303	59,303	59,303
Potential heat-supply from CHP unit, kWh_T/year	15,529	53,252	115,459	255,114	285,324
Heat-unused by the chiller, kWh$_T$/year	4,640	22,438	68,572	198,166	227,494
Heat-shortfall to the chiller, kWh$_T$/year	48,414	28,490	12,415	2,355	1,473
Heat-supplied to the chiller, kWh$_T$/year	10,889	30,813	46,887	56,948	57,830
Cost of equivalent electrical cooling, £/year	70	197	302	367	373

Table 6.4: Heat exchanges between the CHP unit and the chiller [18].

The results of the simulations run for different CHP unit sizes are summarised in Table 6.3. Table 6.4 shows the extent to which the CHP unit satisfies the chillers heat-demand and so provides an indication of the effectiveness of integrating these two technologies. From Table 6.3 it can be seen that the optimal choice of system based on pay-back period is a 150 kW_e CHP unit. The results are based on the following utility rates at the site as of August 1996; gas[1] 14.0p/therm and electricity 4,92p/kWh..

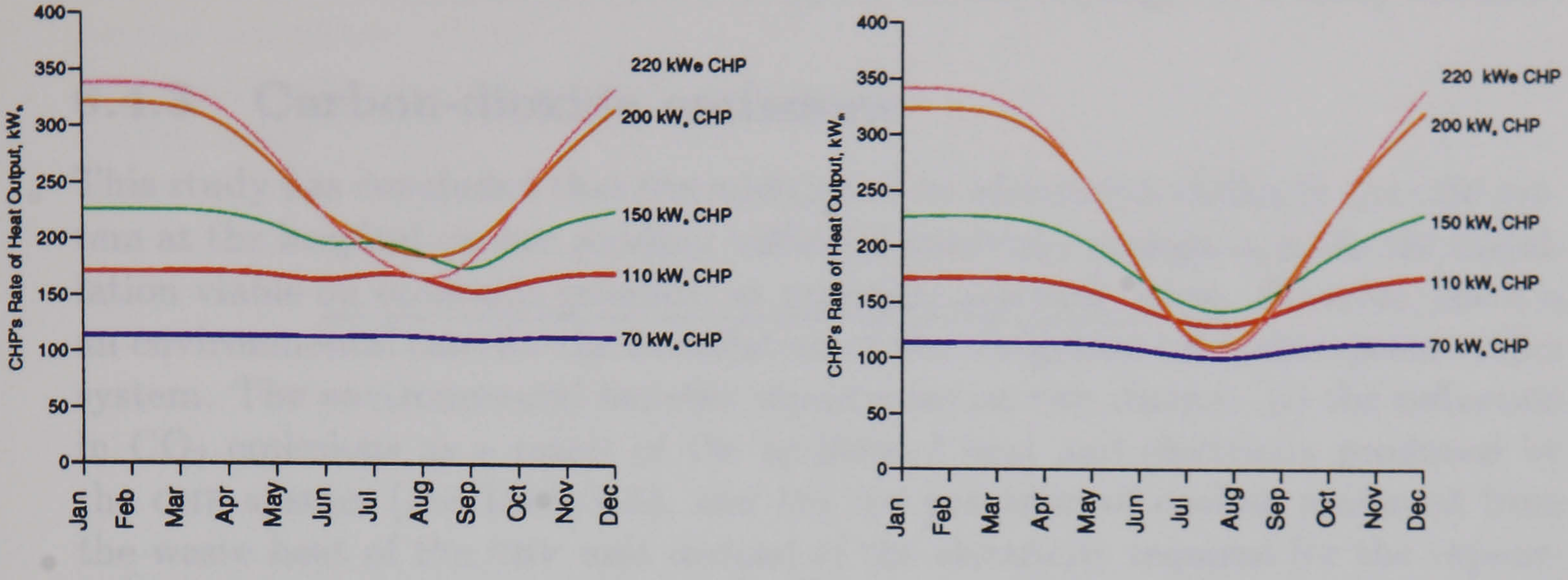


Figure 6.19: Behaviour of the chosen CHP unit with, and without an absorption chiller[18].

Figure 6.19 show the profiles of average monthly **electrical-power** outputs over the year for the different CHP-unit sizes. The sizes are quoted in rated maximum **electrical** outputs of the CHP-units in the figures, i.e. from a $70kW_e$ to a $220kW_e$ CHP unit. These show the extent of modulation necessary over the year. Comparing the figures shows the chillers effect on the degree of CHP modulation needed. The integration of the absorption chiller with the 150kW$_e$ CHP unit will result in a higher electrical output from April to November - see Figure 6.20.

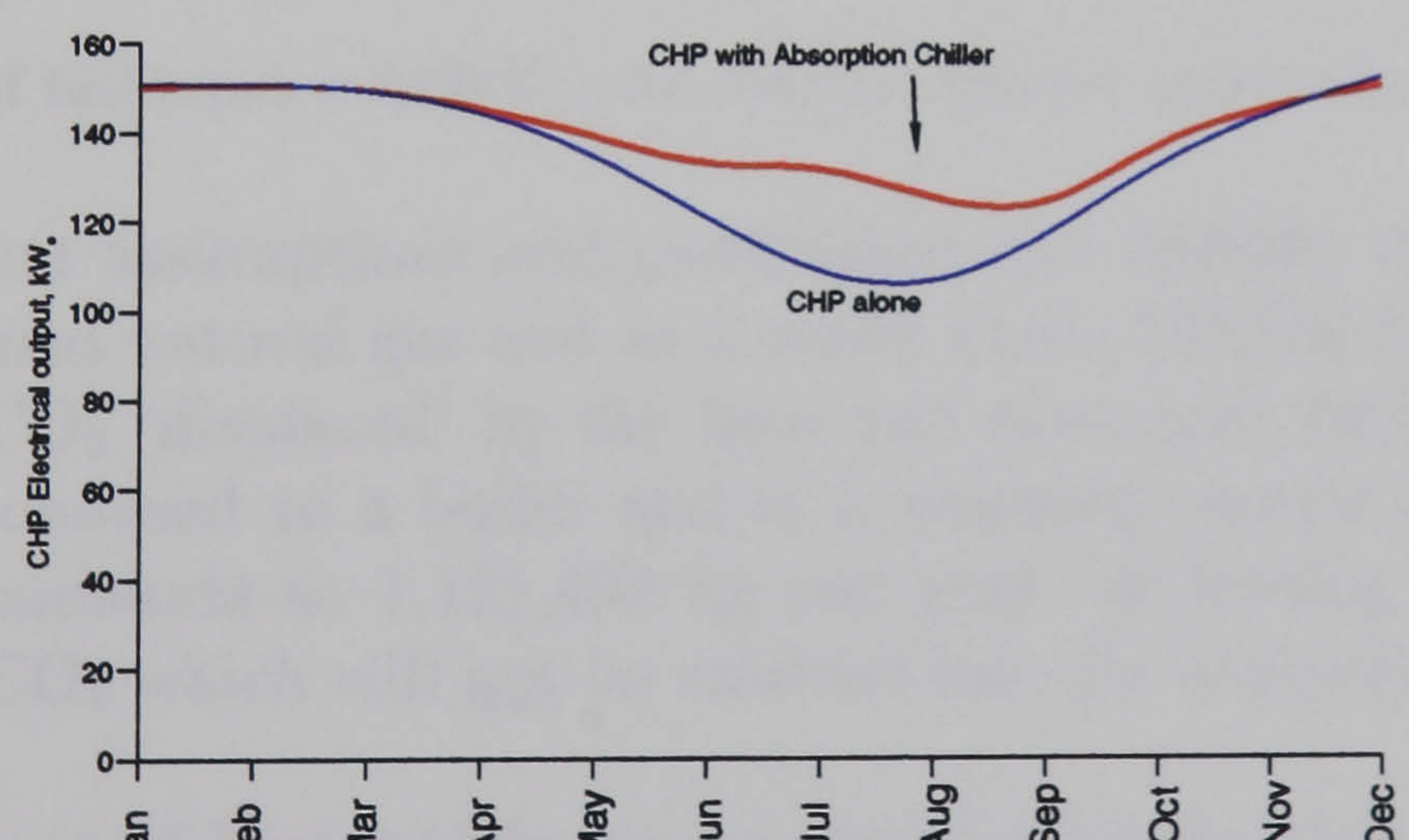


Figure 6.20: CHP electricity output with, and without, an absorption chiller introduced into the system [18].

Combining CHP with absorption cooling has very little effect on the economic savings and adds significantly to the capital cost of the installation. Also, at the

[1]Gross calorific value = 105.5 MJ/therm.

optimal CHP unit size, there is an annual short-fall of heat to the chiller of 21% per annum (see Table 6.4). This means that the existing vapour-compression units must be retained and maintained to supplement the cooling, i.e. a costly scenario.

6.4.3 Carbon-dioxide emissions

This study has concluded that the addition of an absorption chiller to the CHP system at the hospital cannot produce sufficient monetary savings to make the installation viable on economic grounds, as presently assessed, alone. However, there is an environmental case for the installation of the integrated CHP/absorption chiller system. The environmental benefits would arise on two counts:- (i) the reduction in CO_2 emissions as a result of the additional heat and electricity produced by the CHP system (see Table 6.5), and (ii) the provision of cooling produced from the waste heat of the CHP unit instead of the electricity required for the vapour-compression units. This will also displace some of the potential for CFC's being released into the atmosphere.

	CO_2 (kg) emission as a result of the production of 150 kWh of electricity and 226kWh of heat.		
	Electricity	**Heat**	**Total**
Separate Heat and Electricity production	148.5 [2]	58.7 [3]	207.2
Combined Heat-and-Power	-	-	99.4 [4]

Table 6.5: Typical CO_2 emissions from the two different energy-release processes.

[2] Assuming 0.99kg CO_e emitted for each kWh of electricity.

[3] Assuming a boiler efficiency of 75% and the emission of 5.711 kg CO_2 for each therm of gas burnt.

[4] Assumed rate of fuel input = 510kW; CHP overall efficiency approximately 80%

From the present assumptions and predictions, the $150kW_e$ CHP unit installed at the hospital burns natural gas and as a result emits 545,156 kg of CO_2 each year. However, the CO_2 'displaced' by the heat and electricity being generated by the CHP unit - as opposed to a boiler and of a separate central electricity generator respectively - amounts to 1,121,463 kg per year, so leading to a net benefit of 576,307 kg of CO_2 which will not be emitted into the atmosphere each year.

The total amount of heat which can be supplied to the chiller from the $150kW_e$ CHP unit, before the chiller is added to the system, amounts to 46,887 kWh each year. However, once the chillers demand for heat, in order to supply chilled water to the wards and other rooms, is added to the hospital's summer heat-demand for hot-water, then the total yearly heat produced by the CHP unit increases by 75,787kWh. This is significantly more than the 46.887 kWh of potential heat supply to the chiller. Additionally, the electricity output from the CHP unit also increases by 50,050 kWh per year. The combined system produces more useful energy than the sum of the outputs from the two individual systems. This is because the additional heat-demand in summer from the chiller increases the demand for heat from the CHP unit to above 50% of its maximum rated heat-output on several occasions. Consequently, the CHP unit will not switch-off automatically for as many hourly periods as would have been the case without the absorption chiller being in place. The additional operational hours and output levels also allow more electricity to be produced and consumed in the hospital's ring-main circuit. There is always a greater demand for electricity across the hospital than the total potential supply of electricity from the three CHP units combined.

Annual CO_2 savings as a result of employing the integrated system.

Annual CO_2 Emissions arising from Separate Electricity and Heat Production versus Annual CO_2 Emissions arising from CHP and CHP+absorption chiller Systems			
150 kW_e CHP unit only			
	Electricity, (kg CO_2)	Heat, (kg CO_2)	Total, (kg CO_2)
CHP			545,156
Separate heat and power	803,662	317,801	1,121,463
Net benefit of employing CHP			576,307
150 kW_e CHP Unit plus absorption chiller			
	Electricity, (kg CO_2)	Heat, (kg CO_2)	Total, (kg CO_2)
CHP			577,790
Separate heat and power	853,212 + 5,473*	325,609	1,183,897
Net benefit of employing CHP			605,504
Annual net benefit of the absorption chiller			
	Electricity, (kg CO_2)	Heat, (kg CO_2)	Total, (kg CO_2)
Net benefit			29,197

Table 6.6: Annual CO_2 Emissions for alternative energy-supply strategies for the hospital.

* Note that this value for CO_2 emissions is equivalent to the 6,138 kW_e required to provide the same cooling effect as that provided by the heat-driven absorption chiller.

The additional heat-output from the CHP unit displaced 28,521 kWh of heating at the hospital, thus saving 5,851 kg of CO_2 from being produced and 6,138 kWh of electrically-produced cooling thereby saving another 5,473 kg of CO_2 annually. Annually, the additional 50,050 kWh of CHP-produced electricity displaced 49,550 kg of CO_2. The total CO_2 displaced amounts to 60,873 kg per year. When the additional CO_2 emitted from the CHP unit is subtracted from the 60,873 kg, a net saving annually of 29,197 kg of CO_2 is saved through using the integrated system. This amounts to a further 5% reduction of CO_2 emitted annually to the atmosphere over-and-above that achieved by using the CHP unit alone. This CO_2

saving is proportional to the higher useful energy output from the CHP unit, and arises as a result of the more effective use of fuel.

6.4.4 Comments on the Study and Findings

The air-conditioning (AC) requirement for phase 3 of the hospital is very small: this renders the CHP-unit/absorption chiller combination uneconomic from the outset for this application at this present time. The life-time savings as a result of using absorption chilling are minute compared with the cost of the chiller and with the savings from the use of the CHP alone. The presence of the chiller does not enhance the economic case for installing CHP in this instance. The simple pay-back period for the optimal unit-size CHP unit in combination with an absorption chiller then exceeds four years. Also, in the present simplified analysis, the cost of the following items were ignored: chilled-water piping to the zones of the building that need cooling, fan-coil units in those areas, as well as the costs of the installation of the chiller, cooling tower and distribution system. Altogether, these expenditures may exceed the chillers cost. The chillers installation cost is especially high because the unit cannot be assembled on site as this would compromise the machine's vacuum. Also, the existing distribution trenches from the boiler-room cannot accommodate the chilled-water piping: separate trenches would be needed and constructing these would be costly, especially considering the disruption to the hospital's operation during installation. The possibility of capital cost reductions for absorption chillers is under investigation. The opportunity for cost reduction through the use of low-cost materials has been assessed and considered as viable [98]. Any reduction in the capital cost of the absorption systems will lead to improved economic prospects for the integrated CHP and absorption chiller system.

Conclusions for MKGH

The optimal energy-supply system for phase 3 of the hospital is found to be a $150kW_e$ CHP unit. The optimal simple pay-back period is 2.9 years with an annual saving of £27,000 for 5,777 running-hours per annum. The cooling load, at present, is inadequate to render cost-effective the introduction of an absorption chiller in combination with the CHP unit.

The hospital was built in three phases, with each phase being largely independent with respect to services, i.e. electricity, heating and cooling. A conceivable future scenario would be to integrate the building services for the whole site. The BEMS already covers most of the site. Integration would then allow the installation of a much larger CHP unit, possibly driven by a gas turbine (The maximum electrical demand of the whole site for AD 1995 exceeded $900kW$). Absorption cooling will definitely be more feasible in this scenario, both because of the now substantial cooling load and the higher quality of the recovered heat from the gas-turbine. A double-effect chiller could be used to condition the intake to the turbine, to improve its performance and for space cooling.

6.5 Documented Case Study of an existing integrated small-scale CHP and absorption chiller system

The next case study documents the operation of an integrated small-scale CHP and absorption chiller system. The objective is to determine whether the installed operational-system can produce the required cooling-effect, with significantly less CO_2 emissions per kW_{coolth} than with electrically-driven chillers.

The system under investigation was installed at a site in the South-East of England in 1994 and the configuration is illustrated in Figure 6.21. The site comprised an office block on five floors with an energy requirement for heating and cooling. A $95kW_e$, $165kW_T$ Perkins (de-rated $110kW_e$) 'hot-engine' CHP unit was used together with a $200kW_{coolth}$ Carrier absorption chiller with a COP of approximately 0.70 - see Figures 6.22, 6.23 and Figures F.1 & F.2 in the Appendix. The 'hot-engine' CHP unit will operate with flow temperatures of up to 105°C, although the engine will run more frequently with a flow temperature of about 100°C (considerably higher than standard small-scale reciprocating CHP engines that commonly operate with a flow temperature of 90°C). The CHP engine will have a lower electrical output as a consequence of the increased hot-water temperatures in the engine.

The total installation cost of the system was about £200,000, with a grant of approximately £30,000. The installed operating configuration allowed the hot-water from the CHP unit to be heated to 105°C by the on-site boilers if the flow temperatures were insufficient to allow the desired operating output from the absorption chiller. The temperature drop across the absorption chiller is approximately 5°C. Therefore, it is necessary to remove heat from the return-water to the CHP unit so that it can operate with maximum effect. This is achieved by taking heat from the water returning from the absorption chiller and using it to pre-heat the boiler feed-water. The absorption chiller is installed in series with two 210 kW_T vapour-compression units, and is operated as the lead-chiller, with the VC units switched on and off as required. The system is fitted with an air-blast cooler, which costs £18,000 more than a standard 'wet-cooling-tower', and will also demand more electricity to operate the fan motors than would be consumed in the 'wet-system'. The 'air-blast' cooling system is used as an alternative to the 'wet-system' in order to reduce maintenance costs and prevent the risk of Legionella bacteria forming in the evaporating water.

The effectiveness of this integrated small-scale CHP and absorption system has been assessed in terms of the carbon-dioxide emissions produced for each kWh of coolth delivered. Several assumptions concerning the system and the operation of its components have been made for simplicity and to ensure that equivalent comparisons are made where possible.

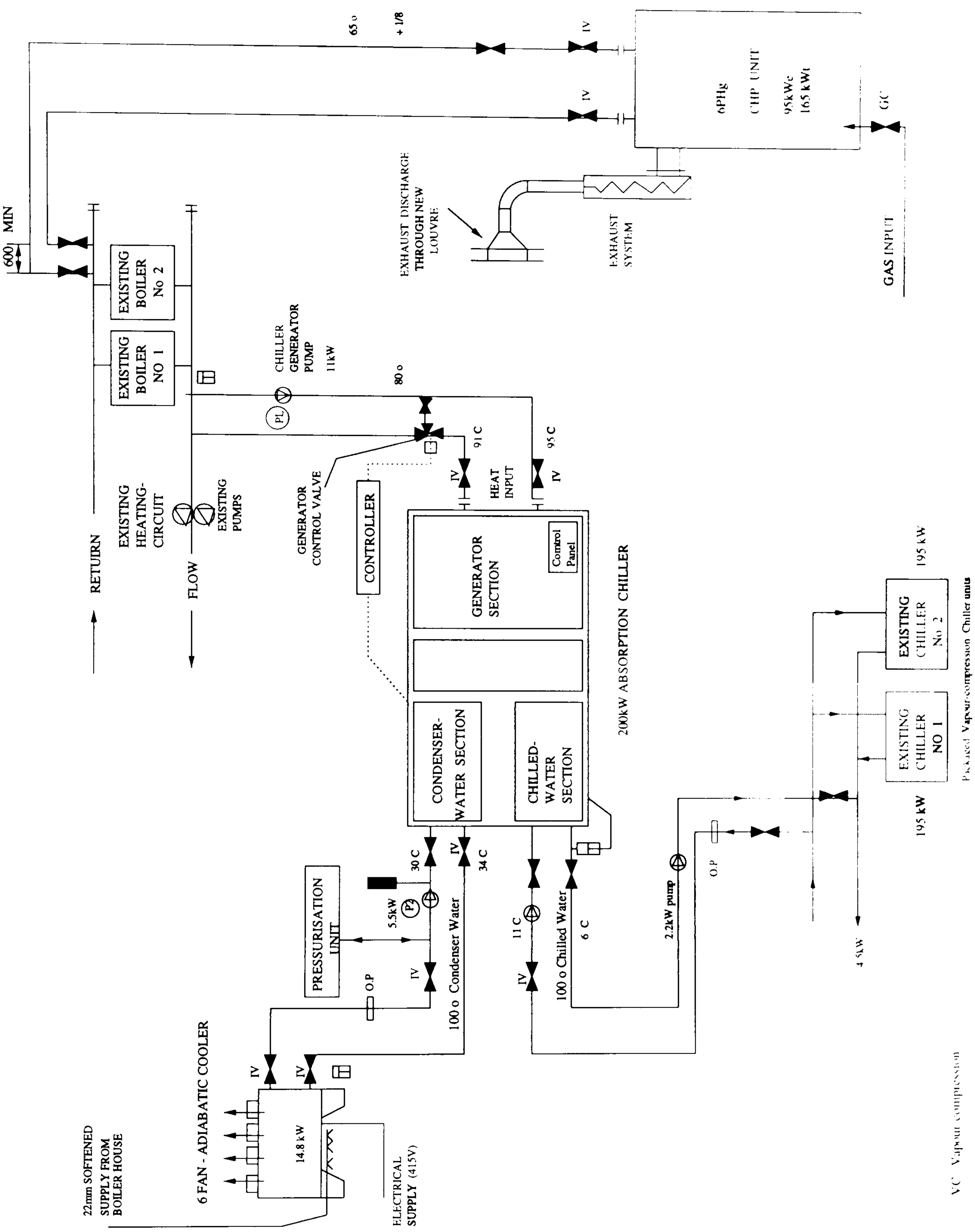


Figure 6.21: Schematic of the installed integrated CHP and absorption system.

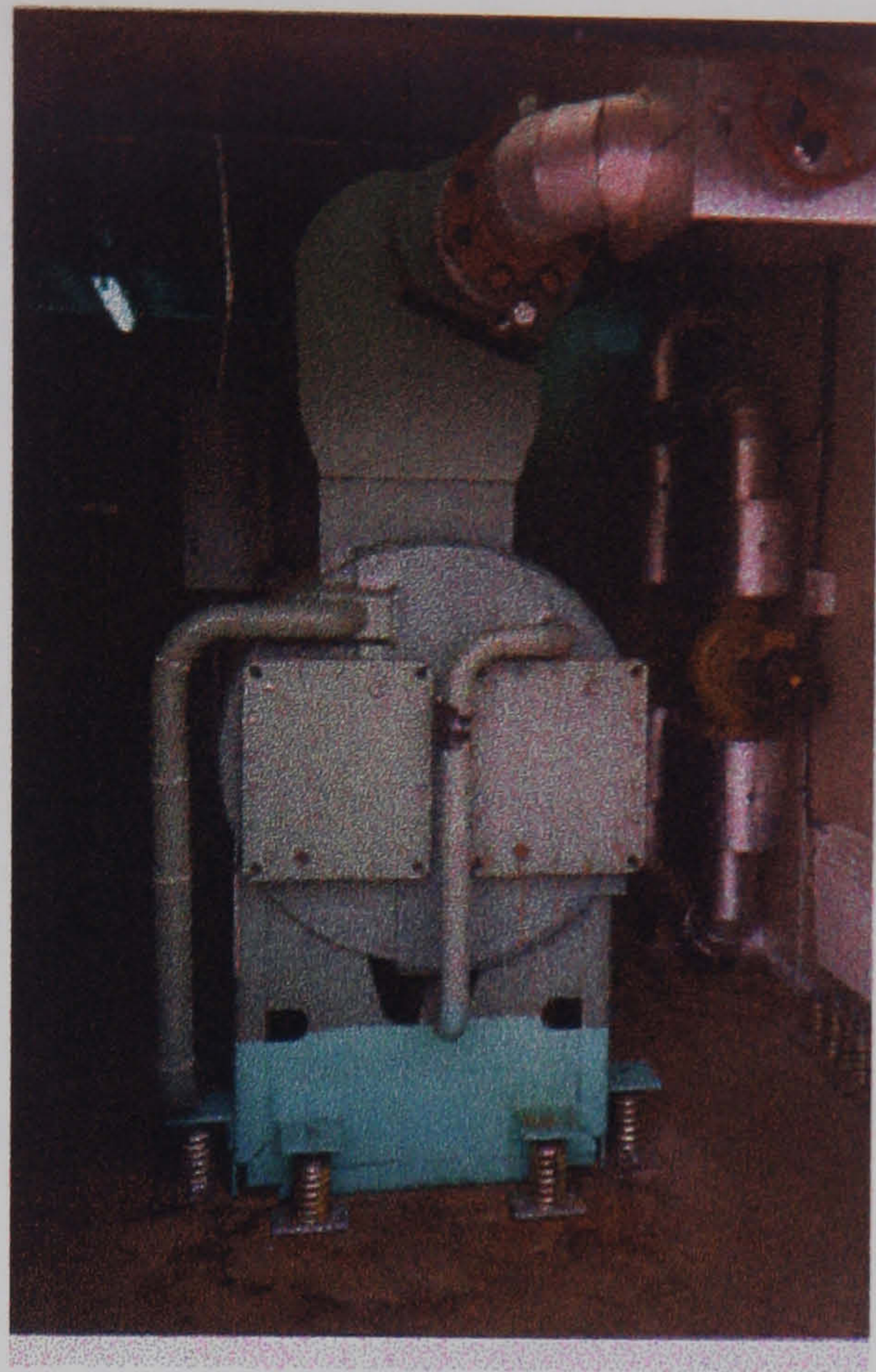


Figure 6.22: Photograph of the absorption chiller as installed at the site.

Figure 6.23: Photograph of cooling fans, as installed at the site.

System : Design Conditions & Assumptions

A schematic showing the arrangements of all of the major components of the integrated small-scale CHP and absorption chiller system can be found in Figure 6.21. Carbon-dioxide emissions will be considered, in terms of kg/kW$_{Coolth}$, for the integrated CHP and absorption system.

Absorption chiller.

Chiller type:	*Carrier* 16JB012
Cooling capacity:	200kW
Chilled water temp:	6°C Flow 11°C Return
Heat input:	294kW
Evaporator:	2 pass LiBr

Combined Heat-and-Power unit.

Unit type:	6pHg high temperature unit
Electrical output:	95kW$_e$ de-rated engine
Heat output:	165kW
Flow water temperature:	90 to 100 °C
Return water temp:	85 to 90°C
Fuel input:	321kW [101]
Noise level:	80 dBA at 1 meter

Adiabatic (Evaporative) Cooler.

Unit type:	Richard Van Spall Adiamatic Dry cooling with limited spray usage
Cooling water temperature	30°C

Pumping and fan power

Type of pump	Maximum Electrical Rating, kW
Internal solution and refrigerant pumps	3.8
Cooling-water pump	5.5
Chilled-water pump	2.2
Generator pumps	11.0
Fan pumps	14.8

Table 6.7: Installed pump and fan maximum power ratings for the installed CHP and absorption chiller system.

Assumptions

American Refrigeration Standard conditions.
ARI 560 - Air Conditioning and Refrigeration Institute.

Chilled water:	12.2 to 6.7°C (0.043 Litres/s per kW_{coolth})
Cooling water:	29.4°C (0.081 Litres/s per kW_{coolth})
Fouling factor:	0.000044 m^3/h - °C/W
Marginal CO_2 emissions of UK electricity generation:	0.990kg CO_2/kWh
Average CO_2 emissions of UK electricity generation:	0.684kg CO_2/kWh
Return cooling-water temperature:	28°C

Additionally No import or export of electricity.
No coolth storage.
Temperature drop across the absorption chiller is 4 to 6°C.
On and off CHP water-temperatures are 95° C and 91° C.

Note: The electrical efficiencies of the motors used to drive the pumps and fans, for each of the three systems are assumed to be equal- as electrical demands of the motors used in the three systems are similar and, therefore, the effects of varying electrical-efficiencies due to different motor sizes are insignificant in this study.

Methodology for CO_2 Analysis

Some preliminary calculations concerning the comparison of CO_2 emissions from CHP or boiler-fired absorption systems and electrically-driven vapour-compression units (at design conditions) have been undertaken for the five systems below:

1. 95 kW_e, 165 kW_T combined heat-and-power + 196 kW_{coolth} absorption chiller + 129 kW Boiler
2. 294 kW Boiler + 200 kW_{coolth} absorption chiller
3. 164 kW_e CHP[5] + 294 kW_{coolth} absorption chiller
4. Electrically-driven vapour-compression unit - refrigerant R22.
5. Electrically-driven vapour-compression unit - refrigerant 134a.

[5]Not actual manufactured unit - specifications have been drawn pro-rata from a similarly sized 145 kW_e CHP unit.

Power demands of 22.4kW and 8.2 kW have been assumed for the parasitic loads of the absorption and vapour-compressions systems respectively - see following pages for a more detailed explanation of these figures. It is also assumed that the CHP unit and absorption chiller are operating at constant-load conditions.

Following the initial estimates for the CO_2 emissions per kWh_{coolth} at design conditions for the five systems, the analysis will be extended to include variations of the source and cooling water temperatures.

System 1 presents the integrated CHP and absorption units as they are installed at the site - see Figure 6.21 for a detailed schematic of the system layout and Figure 6.24 for an overview of the system. System 3 represents the site with a larger, 164 kW_e, 294 kW_T CHP unit installed, so that it can supply all of the heat required by the absorption chiller. The heat required for the absorption chiller in System 2 is provided by a gas-fired boiler only, with the electricity for the parasitic loads taken from the grid. Systems 4 and 5 use similarly sized electrically-driven vapour compression units, with refrigerants R22 and R134a respectively, to supply the desired cooling. The power required for the parasitic load in these cases will also be provided by the grid.

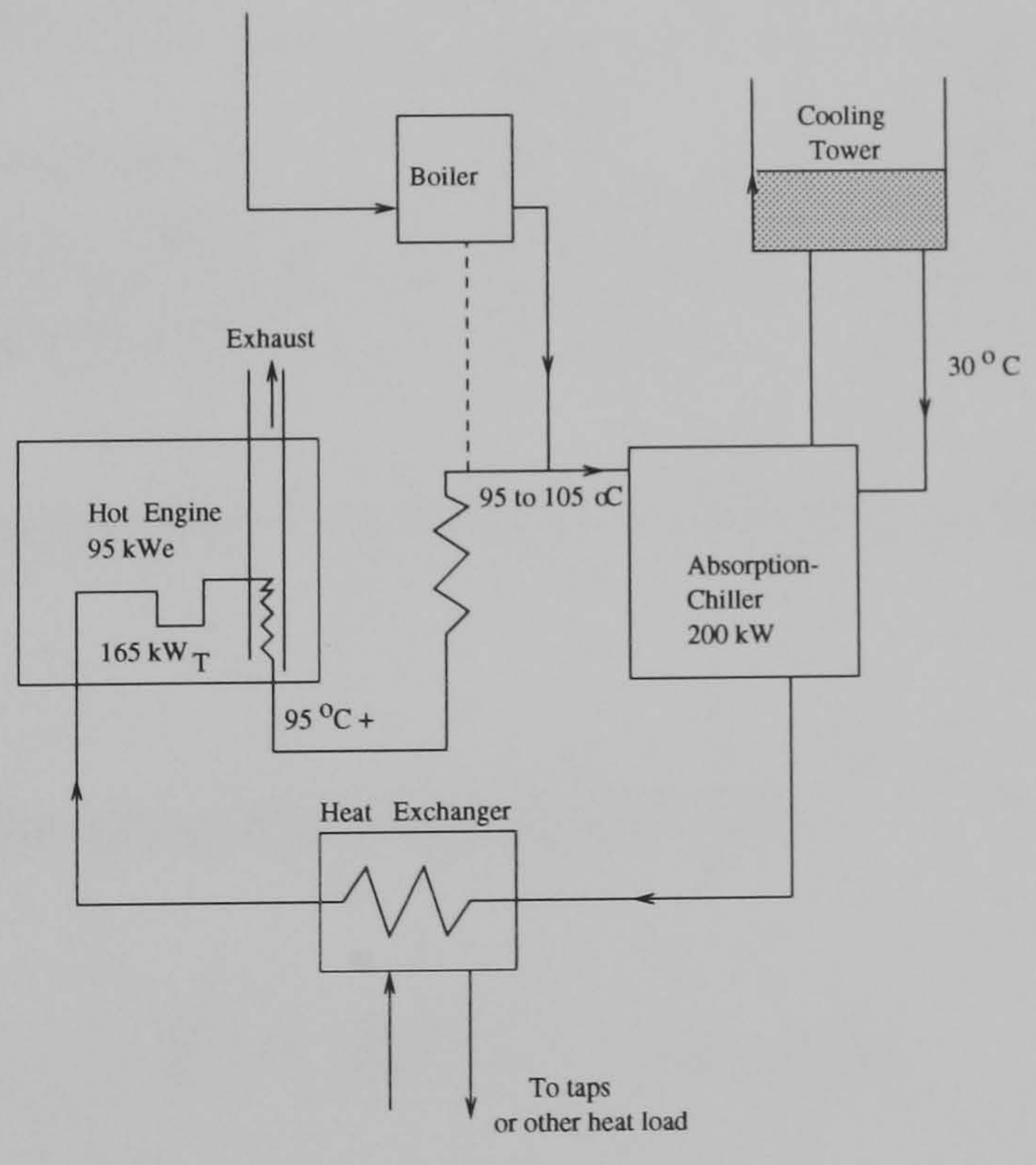


Figure 6.24: Schematic of integrated CHP and absorption system.

6.5.1 Variation of pumping power

The specified electricity consumptions of each of the parasitic loads (i.e. the power to drive the fans and pumps) in the system has not been measured accurately as part of a monitoring programme (for their individual ratings refer to Table 6.7). Therefore, it is not possible to determine the exact power-consumption of the system. Table 6.8 gives an indication of the likely power consumptions for the specified load and equipment conditions, when considering the mass-flow rates of the fluids and the pressure-drop across different sections of the system. The predicted figure of 11.4kW falls well short of the combined power-ratings of each of the individual pumps in the system (at maximum load). However, it is unlikely that the system will operate at full-load conditions for more than a few hours each week.

	Flow rate, (litres/s)	Pressure drop , Δp (kPa)	Pumping power, (kW)
Generator	18	50	0.9
Generator circuit	18	200	3.6
Generator total, kW			4.5
Condenser	25.5	168	4.3
Cooling water circuit	25.5	70.5	1.8
Condenser total, kW			6.1
Evaporator	10	40	0.4
Chilled water circuit	10	40	0.4
Evaporator total, kW			0.8
Total pumping power			11.4

Table 6.8: Pumping power for the generator, condenser and chilled-water systems.

The power required for pumping is calculated from:

$$P = \Delta p \ \dot{V} = \Delta p \ \dot{m}/\rho_w \tag{6.18}$$

where P is: power; Δp is change in pressure across the designated section of the system; $\dot{V}$ is volume-flow rate through the section; $\dot{m}$ is mass-flow rate through the system and ρ_w is density of water.

To analyse the full range of operating conditions, a parametric analysis has been undertaken with the power consumption of the parasitic loads varying as seen in Table 6.9. The cooling and chilled water pumps in the air-conditioning system are set up for single-speed and constant-flow. The cooling water pump power ($CWPP$) is $5.5kW$ and the chilled water pump power ($ChWPP$) is $2.2kW$. The two internal refrigerant and solution pumps incorporated within the absorption chiller also work at constant power- the solution and refrigerant pump power ($SRPP$) is $3.8kW$. Only the fan unit power (FP) and generator pump power (GPP) operate with varying power demands given as:

$$6.4\ kW \leq FP \leq 14.8\ kW \tag{6.19}$$

$$4.5\ kW \leq GPP \leq 11.0\ kW \tag{6.20}$$

The parasitic loads for the vapour-compression and absorption chiller systems will be determined according to the following:

$$\text{VC}\ Parasitic\ load = 0.5(FP + CWPP) + ChWPP \tag{6.21}$$

$$\text{AC}\ Parasitic\ load = FP + CWPP + ChWPP + GPP + SRPP \tag{6.22}$$

	P_{min}	P_2	P_3	P_4	P_{max}
Fan Power, kW	6.4	8.5	10.6	12.7	14.8
Cooling-water pump, kW	5.5	5.5	5.5	5.5	5.5
Chilled-water pump, kW	2.2	2.2	2.2	2.2	2.2
Generator pump, kW	4.5	6.1	7.8	9.4	11.0
Solution/refrigerant pump, kW	3.8	3.8	3.8	3.8	3.8
Absorption chiller total, kW	22.4	26.1	29.9	33.6	37.3
Vapour-compression chiller total, kW	8.2	9.2	10.3	11.3	12.4

Table 6.9: Range of parasitic power requirements for the absorption and vapour-compression chiller systems.

Table 6.9 presents the range of power consumptions from P_{min} to P_{max} for the integrated CHP/absorption chiller and vapour-compressor chiller systems. It is assumed that increasing the electrical power consumption of one of the components in the system will mean that additional power is required for the other pumps - reasonable as each of the individual processes in the integrated system are linked.

The parasitic power consumption for the absorption systems and resultant hourly CO_2 emissions will be assumed to lie in the ranges respectively[6]:

$$22.4\ kW \leq P \leq 37.3\ kW \tag{6.23}$$
$$22.2\ kg/hour \leq CO_2 \leq 36.9\ kg/hour \tag{6.24}$$

For the VC systems, it can be assumed that parasitic power consumption and resultant CO_2 emissions will lie in the ranges:

$$8.2\ kW \leq P \leq 12.4\ kW \tag{6.25}$$
$$8.1\ kg/hour \leq CO_2 \leq 12.3\ kg/hour \tag{6.26}$$

The COP for the absorption chiller is predicted without the inclusion of the energy demanded by the parasitic loads (composed of fans ($14.8kW$), generator pump ($11.0kW$), cooling-water pump ($5.5kW$), chilled-water pump ($2.2kW$), and internal refrigerant and solution pumps ($3.8kW$).

6.5.2 Carbon-Dioxide Emission Analysis.

In the following work, the minimum power P_{min} - which is considered as a realistic estimate for the various pumps by the site's operators - will be taken as the parasitic-load for both the absorption chiller and the vapour-compression systems.

The study will now continue by analysing CO_2 emissions for systems 1 to 5 under several different operating conditions. Initially the level of carbon-dioxide emissions per kWh_{coolth} will be examined for the five separate systems with parasitic-loads for the absorption chiller and vapour-compression systems assumed at 22.4 kW and 8.2 kW respectively. The procedure used in the evaluation will be presented in detail. A brief analysis of the effect of increasing the parasitic power consumption will then be undertaken. Finally the level of CO_2 emissions for varying source and cooling water temperatures will be determined for minimum and maximum parasitic power loads.

[6]Assuming 990g CO_2 emissions per kWh_e from central electricity generation [9].

Methodology for calculations

The level of CO_2 emissions per kWh_{coolth} for each of the five systems will be determined from the sum of one or more of the following.

- The CO_2 emissions for the fuel furn associated with that proportion of electricity and heat - which is provided simultaneously by the CHP unit to the absorption chiller - to satisfy both the electricity demand required by the parasitic load and some of the heat demand. The electrical and thermal efficiencies of the CHP units considered are 29.6% and 51.1% respectively.
- The CO_2 emissions associated with the production of the remaining heat only, used to drive the absorption chiller, from the CHP unit. The remaining unused electricity from the CHP unit will be set against the electricity produced in a steam turbine with a generating efficiency of 35% [102]. The difference between the two systems, in terms of electricity generated, will be allocated as the cost (representing the CO_2 emissions associated with fuel burn) of the remaining heat supplied by the CHP unit.
- The CO_2 emissions associated with the supply of the remaining heat required to drive the absorption chiller from a gas-fired boiler (efficiency 80%).
- The CO_2 emissions associated with the central generation of electricity used to drive the parasitic loads and/or the vapour-compression chillers.

Note: The CO_2 emissions for each kWh of electricity generated will be taken at the marginal rate (i.e. 0.990kg per kWh) and the average rate (i.e. 0.684kg per kWh) [9]. Two examples of the system with a CHP unit and an absorption chiller are considered. In the first case, which represents the site as it is currently set up, only part of the heat demand from the chiller will be supplied by the CHP unit. Whereas, the CHP unit in the System 3 will supply all of the heat required.

System 1:

Combined Heat-and-Power + Absorption Chiller + 129 kW Boiler

This system will operate with a $95kW_e$, $165kW_T$ de-rated gas-fired CHP engine and will require an additional heat input of 129kW from the boiler in order to maintain the desired cooling effect of approximately 200 kW_{coolth} ($196kW_{coolth}$) from the absorption chiller. External auxiliary equipment (i.e. parasitic loads), such as the chilled and cooling water pumps and fans will require further electrical power as follows: Refrigerant pump (2.2kW), cooling water pump (5.5kW), generator pumps (total 11kW). In addition to pumping power, energy will be required for the cooling fans, which have a maximum rating of 14.8kW. The solution and refrigerant pumps operating within the absorption chiller unit will require a further 3.8kW, which will result in a total maximum parasitic load of approximately 37.3kW. However, the fans are rarely operated at maximum and their electrical consumption is on average assumed to be 6.4kW. The electrical consumption of the generator-pump is directly proportional to the amount of cooling output demanded by the site. The average parasitic load for the system will be assumed to be 22.4kW_e as detailed in Table 6.9 .

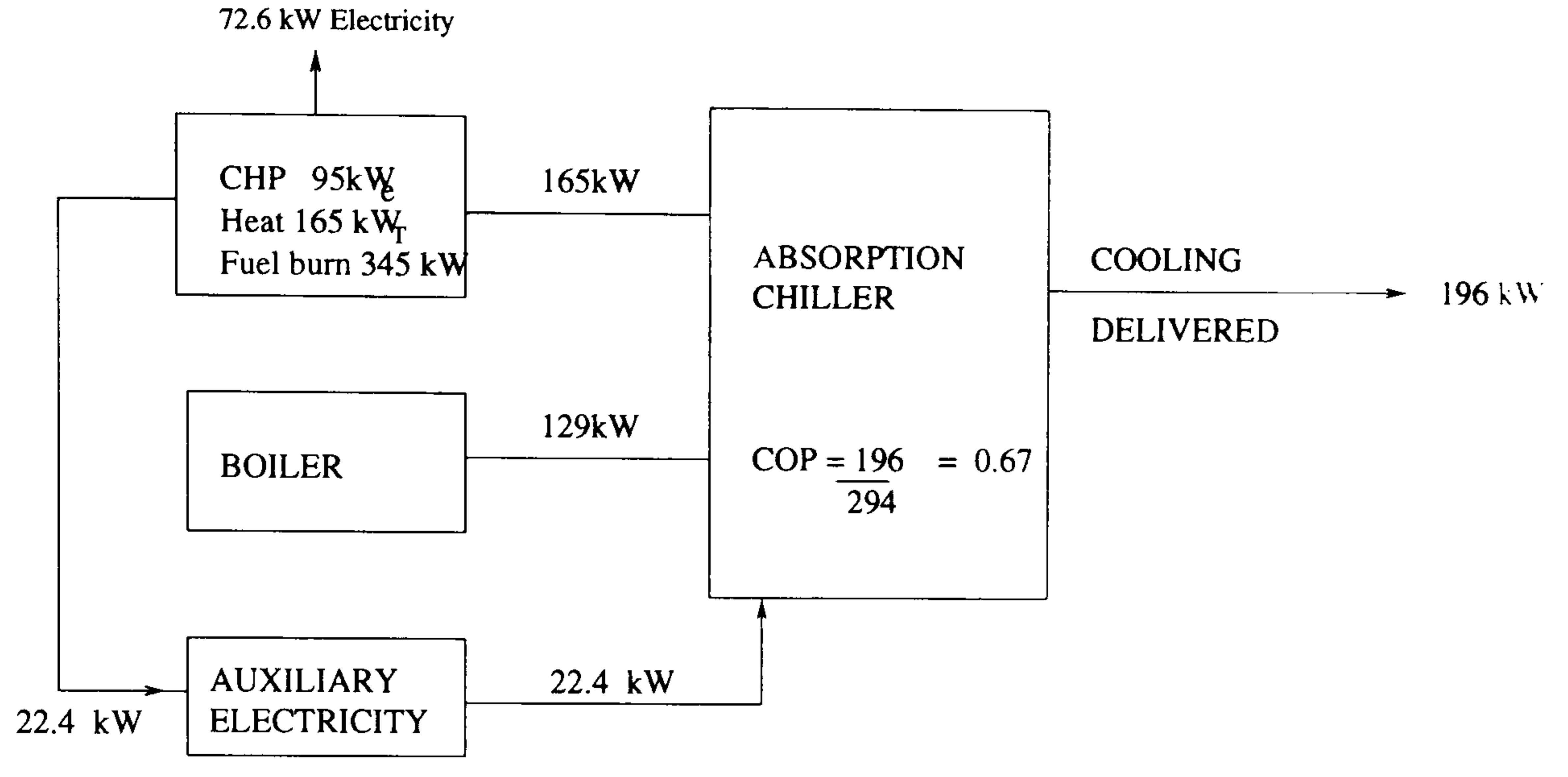


Figure 6.25: SYSTEM 1: Schematic for the CHP-fired absorption chiller with boiler supplement.

The different components that produce CO_2 emission are:

- Fuel burn for the operation of the CHP unit to produce the electricity for the parasitic load (i.e. 22.4kW) and the associated heat output (i.e. 38.9 kW_T) will give rise to the emission of 14.75 kg CO_2/hour when operating at full-load conditions.

- CO_2 emissions associated with the fuel burn in the CHP unit, required to generate the remaining 126 kW_T for supply to the absorption chiller = 13.1 kg CO_2.

- Fuel burn to generate the additional heat output in the boiler (efficiency 80%) gives rise to the emission of 129/(29.3056*0.80) × 5.711 [7] = 31.42 kg CO_2/hour [8].

Total CO_2 produced per hour for 196kW_{coolth} = 14.75 + 13.1 + 31.42 = 59.3 kg CO_2/hour.

This equates to 59.3/196 = <u>0.302 kg CO_2/kWh$_{coolth}$</u>.

[7] 5.711 kg CO_2 will be produced for every therm of natural-gas burnt in the boiler.

[8] 1kWh of electricity generated gives rise to the production of 990g CO_2 (marginal rate) in the UK [9].

System 2:

294 kW_T Boiler + absorption chiller

This system will operate with one large gas-fired boiler to drive the absorption chiller instead of the $95kW_e$ CHP unit. Internal and external auxiliary components will also remain as stated for System 1 with identical electricity consumptions.

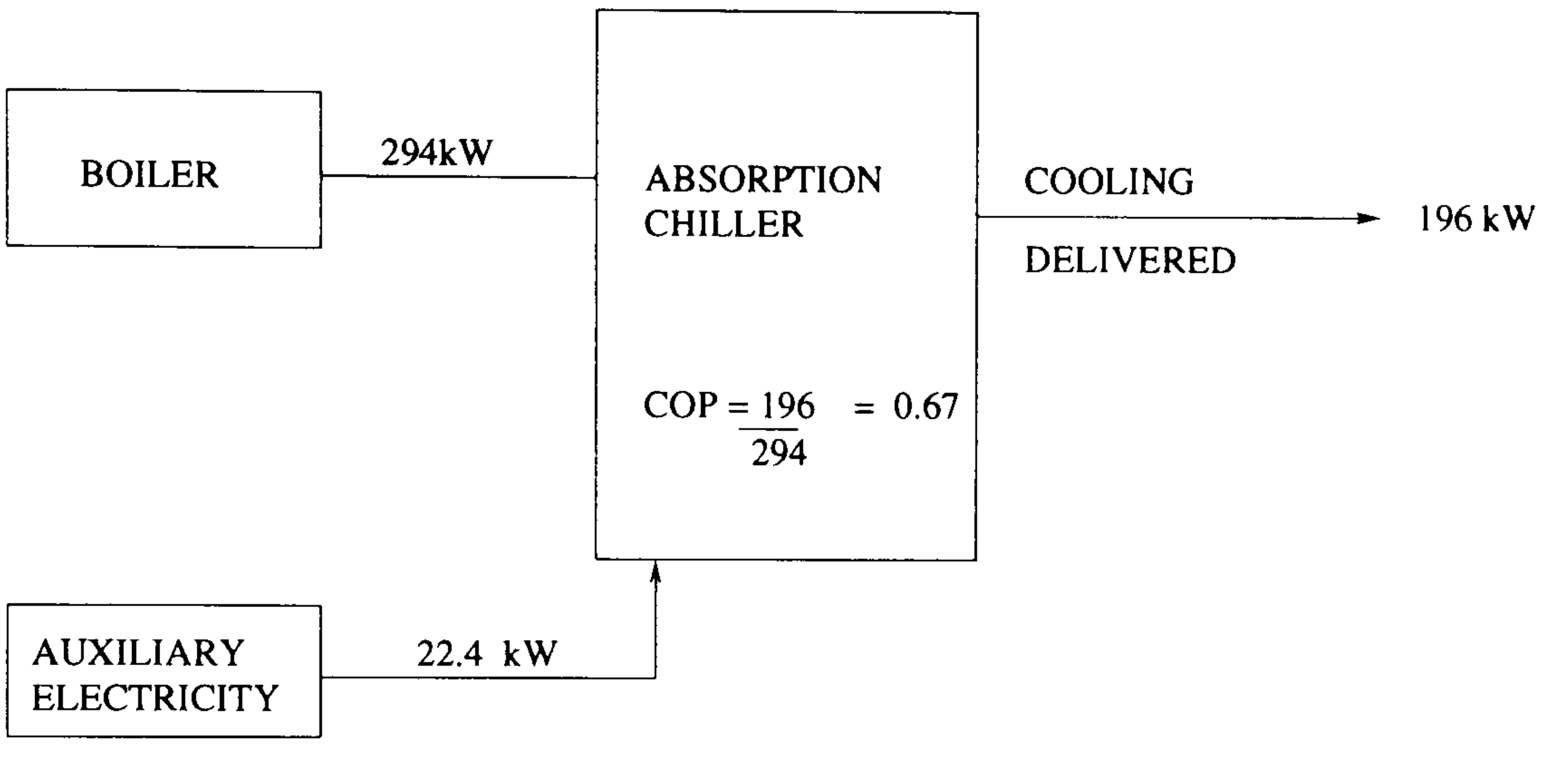


Figure 6.26: SYSTEM 2: Schematic for the boiler-fired Absorption system.

Sources of emissions include:

- Fuel burn to generate the heat output from the boiler (efficiency 80%) will give rise to the emission of $294/(29.3056*0.8) \times 5.711 = 71.61$ kg CO_2/hour.
- Electricity for auxiliary components (22.4 kW maximum operating conditions) produces $22.4 \times 0.990 = 22.2$ kg CO_2/hour.

Total CO_2 produced per hour for $196kW_{coolth} = 71.61 + 22.2 = 93.8$ kg CO_2/hour.

This equates to <u>0.48 kg CO_2/kWh_{coolth}</u>.

System 3:

164 kW_e, 294kW_T CHP + Absorption Chiller

This system will operate with a 164 kW_e, 294kW_T CHP unit to replace the 95 kW_e, 165kW_T CHP unit. The same absorption chiller will remain. Internal and external auxiliary components will also remain as stated in system 1 with the same electrical consumption.

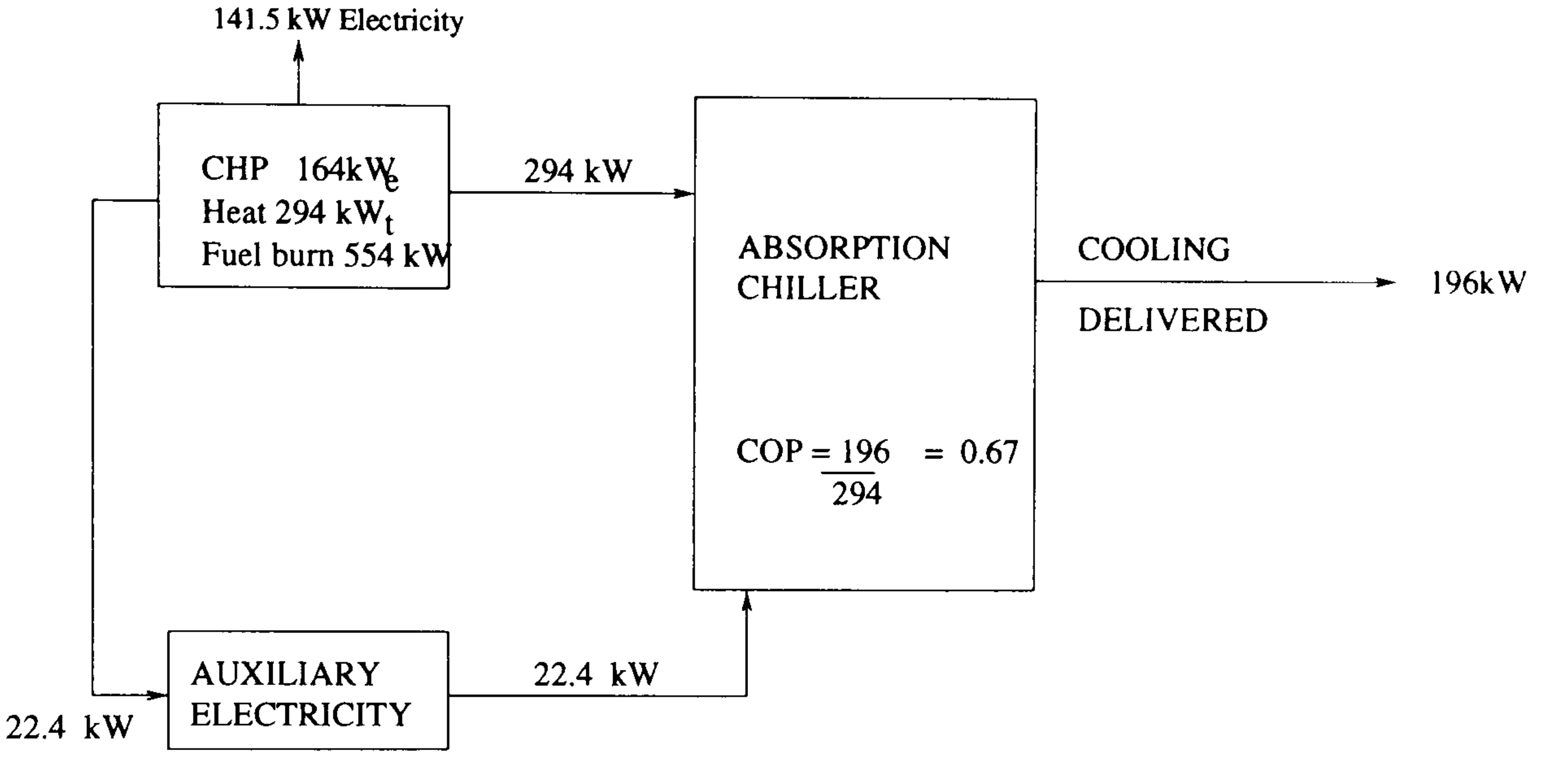


Figure 6.27: SYSTEM 3: Schematic of the CHP-fired absorption system.

Emissions include:

- Fuel burn for the operation of the CHP unit to produce the electricity for the parasitic load (i.e. 22.4kW) and the associated heat output (i.e. 40.1 kW_T) will give rise to the emission of 14.75 kg CO_2/hour when operating at full-load conditions.

- CO_2 emissions associated with the fuel burn in the CHP unit, required to generate the remaining 253.6 kW_T for supply to the absorption chiller = 25.6 kg CO_2 [9].

Total CO_2 produced per hour for 196kW_{coolth} = 14.75 + 25.6 = 40.35 kg CO_2/hour.

This equates to 0.206 kg CO_2/kWh_{coolth}.

[9]Methodology as in System 1.

System 4:

Electrically-Driven Vapour-Compression Unit.

In this system, the cooling effect will be achieved through the use of an electrically-driven chiller. A *CARRIER* 91 water-cooled chiller with R22 refrigerant will be considered [28]. The total average external electrical consumption has been determined to fall in the range 8.2 kW to 12.4kW (chilled-water pump = 2.2 kW and cooling-water pump circuit = 10.2 kW) to operate the chilled-water and cooling-water pumps. As this system is to be compared directly with systems 1, 2 and 3, the total parasitic load used for the calculations will be 8.2 kW. The condenser and chilled-water temperatures are 30°C and 6°C respectively, the cooler and condenser water temperature drop will be 5K.

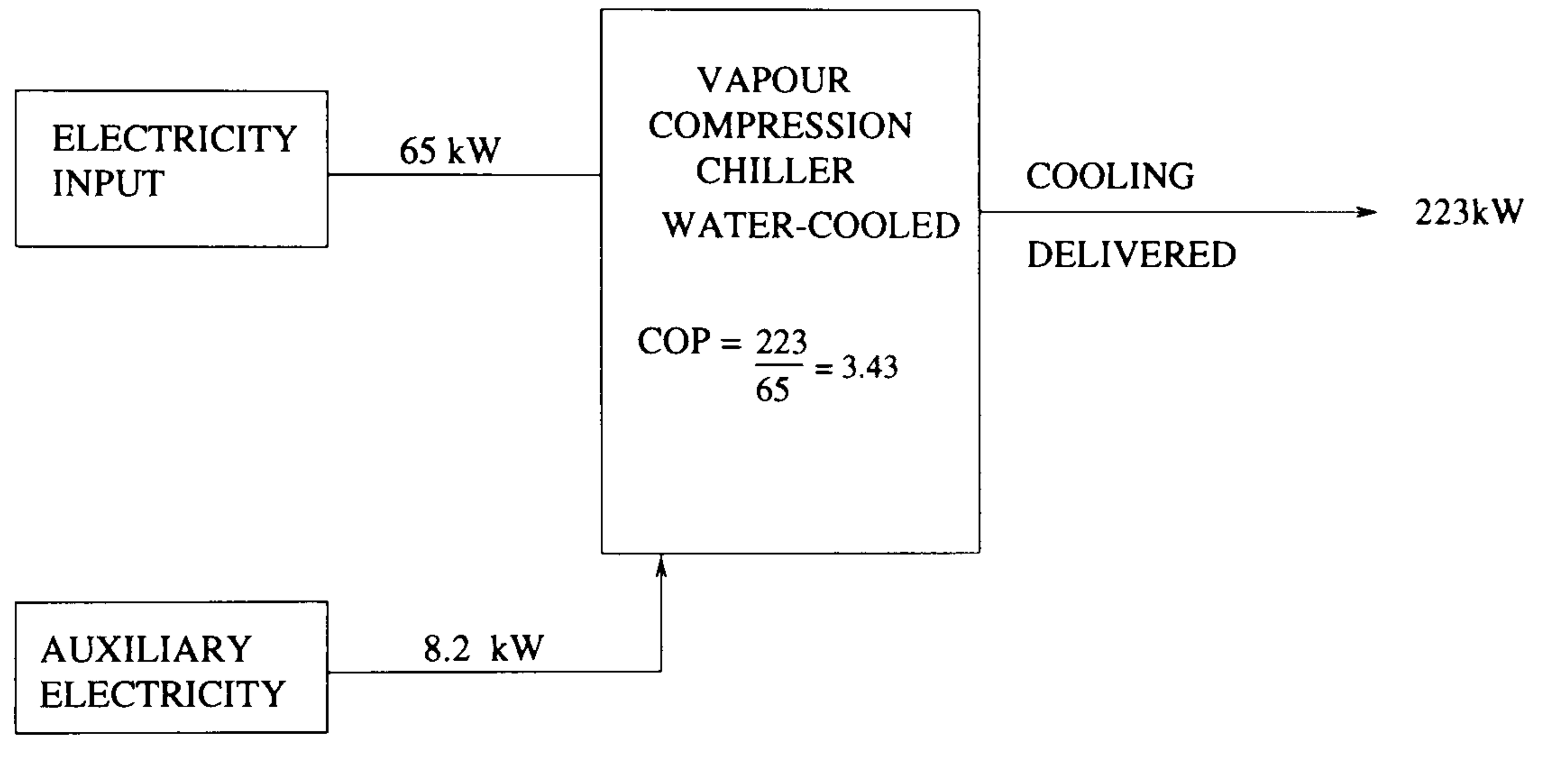


Figure 6.28: SYSTEM 4: Schematic for the electrically driven vapour-compression system.

Sources of emission are:

- CO_2 produced by the electricity used to drive the chiller = $65.0 \times 0.990 =$ 64.4 kg CO_2/hour.
- Electricity for auxiliary components (8.2 kW) produces $8.2 \times 0.990 = 8.1$ kg CO_2/hour.

Total CO_2 produced per hour for 223kW$_{coolth}$ = 64.4 + 8.1 = 72.5 kg CO_2/hour.

This equates to 0.33 kg CO_2/kWh$_{coolth}$.

System 5:

Electrically-Driven Vapour-Compression Unit.

In this system the cooling effect will be achieved through the use of an electrically-driven chiller. A *TRANE* RTAB 110 water-cooled chiller with R134a refrigerant will be considered [103]. The total average external electrical consumption has been determined as 8.2 kW to operate the chilled-water and cooling-water pumps. The condenser and chilled-water temperatures are 30°C and 6°C respectively.

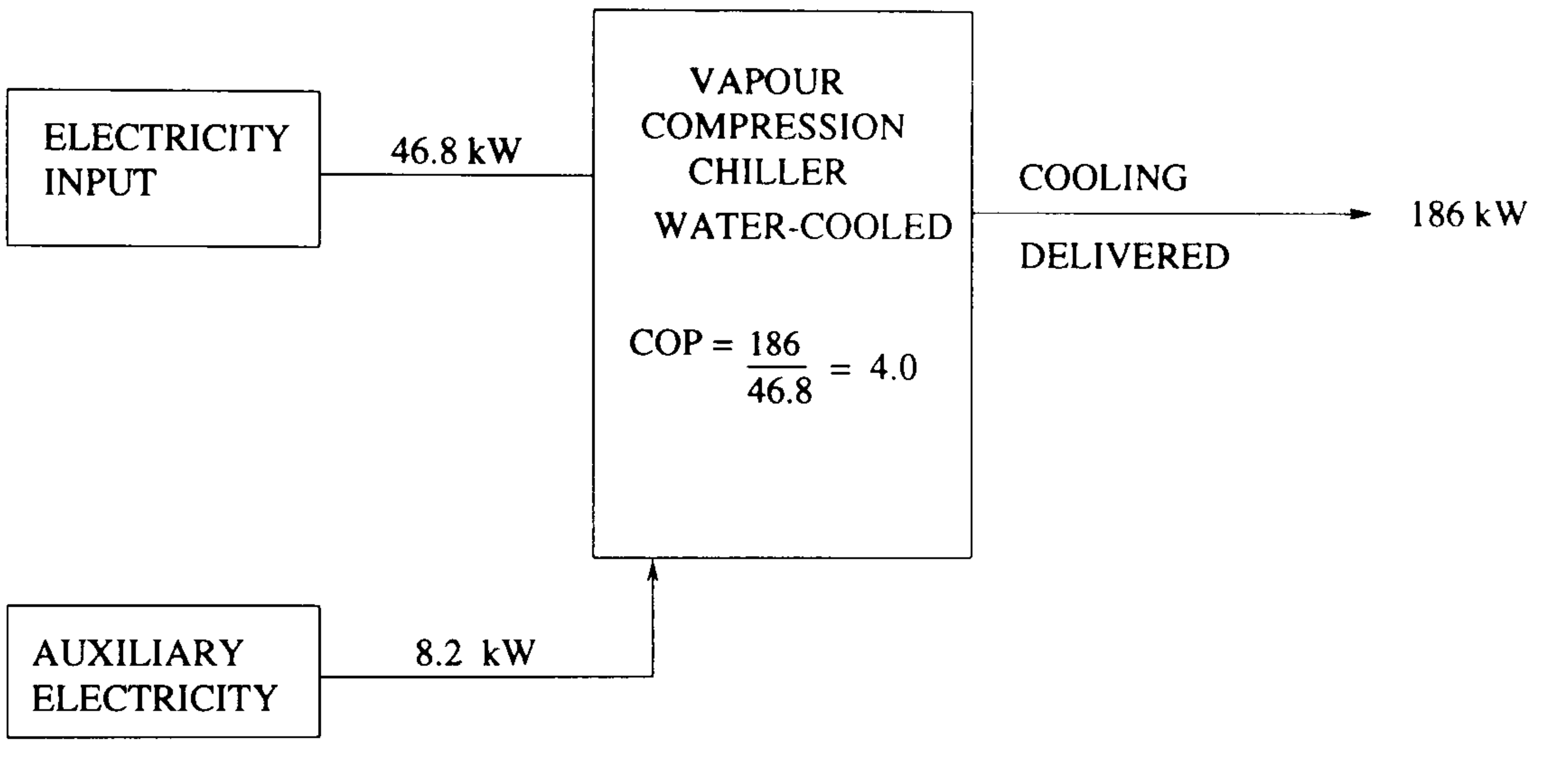


Figure 6.29: SYSTEM 5: Schematic for the electrically driven vapour-compression system.

Sources of emission are:

- CO_2 produced by the electricity used to drive the chiller = 46.8 × 0.990 = 46.3 kg CO_2/hour.
- Electricity for auxiliary components (8.2 kW) produces 8.2 × 0.990 = 8.1 kg CO_2/hour.

Total CO_2 produced per hour for 186kW$_{coolth}$ = 46.3 + 8.1 = 54.4 kg CO_2/hour.

This equates to 0.29 kg CO_2/kWh$_{coolth}$.

The calculations have been repeated for each of the five systems with the average UK generating efficiencies assumed instead of the marginal efficiencies (i.e. only 0.684kg CO_2 will now be emitted for each kWh of electricity generated instead of 0.990kg when the marginal rate is assumed).

System 1: 14.75 + 31.42 + 9.06 = 55.23 kg CO_2 / hour	= 0.28 kg CO_2 / kWh$_{coolth}$.
System 2: 71.61 + 15.32 = 86.9 kg CO_2 / hour	= 0.44 kg CO_2 / kWh$_{coolth}$.
System 3: 14.75 + 17.64 = 32.39 kg CO_2 / hour	= 0.17 kg CO_2 / kWh$_{coolth}$.
System 4: (65 + 8.2) * 0.684 = 50.1 kg CO_2 / hour	= 0.22 kg CO_2 p/kWh$_{coolth}$.
System 5: (46.6 + 8.2) * 0.684 = 37.48 kg CO_2 / hour	= 0.20 kg CO_2 / kWh$_{coolth}$.

Table 6.10: CO_2 emissions for the CHP and absorption chiller system with average fan & pumping power requirements - Average UK generating efficiency is assumed).

	CO_2 Output (kg) per kW$_{coolth}$ produced	
	Case A	Case B
System 1	0.30	0.28
System 2	0.48	0.44
System 3	0.21	0.17
System 4	0.33	0.22
System 5	0.29	0.20

Table 6.11: CO_2 emissions per kWh$_{coolth}$ for each of the five systems.

Notes:

(A) assumes that coal-fired electricity production will be displaced, thus removing 0.990kg of CO_2 emissions for each kWh of electricity generated [9].

(B) assumes that electricity generated at average UK efficiencies will be displaced, thus removing 0.684kg of CO_2 emissions for each kWh of electricity generated [9].

Observations

The current operation of the installed integrated CHP and absorption chiller is represented by system 1. The analysis has predicted that the CO_2 emissions/kWh$_{Coolth}$ from System 1 are greater than those from the VC System 5 (i.e. at +3.4%) and less than those for System 4 (at -9%). Table 6.11 shows that for electricity displaced at the marginal and average rates, System 3, which represents a a system with all of the heat supplied by a large CHP unit, produces the least CO_2 emissions at 0.21 and 0.17 kg/kWh$_{coolth}$ respectively. For each case the highest CO_2 emissions are produced by System 2 - the boiler-fired absorption chiller system.

CO_2 Emissions for varying parasitic loads

Having determined the level of CO_2 emissions from the five systems for a fixed parasitic load at design operating conditions, the effect on the CO_2 emissions of increasing the power demanded by the pumps from P_{min} to P_{max} will now be analysed - see Table 6.12 and Figure 6.30.

	P_{min}	P_2	P_3	P_4	P_{max}
System CO_2 emissions/unit cooling					
System 1: Absorption system, CO_2/kWh	0.302	0.311	0.321	0.330	0.339
System 4: Vapour compression system, CO_2/kWh	0.325	0.329	0.335	0.34	0.344

Table 6.12: CO_2 emissions for a range of parasitic power-requirements for the absorption and vapour-compression chiller systems.

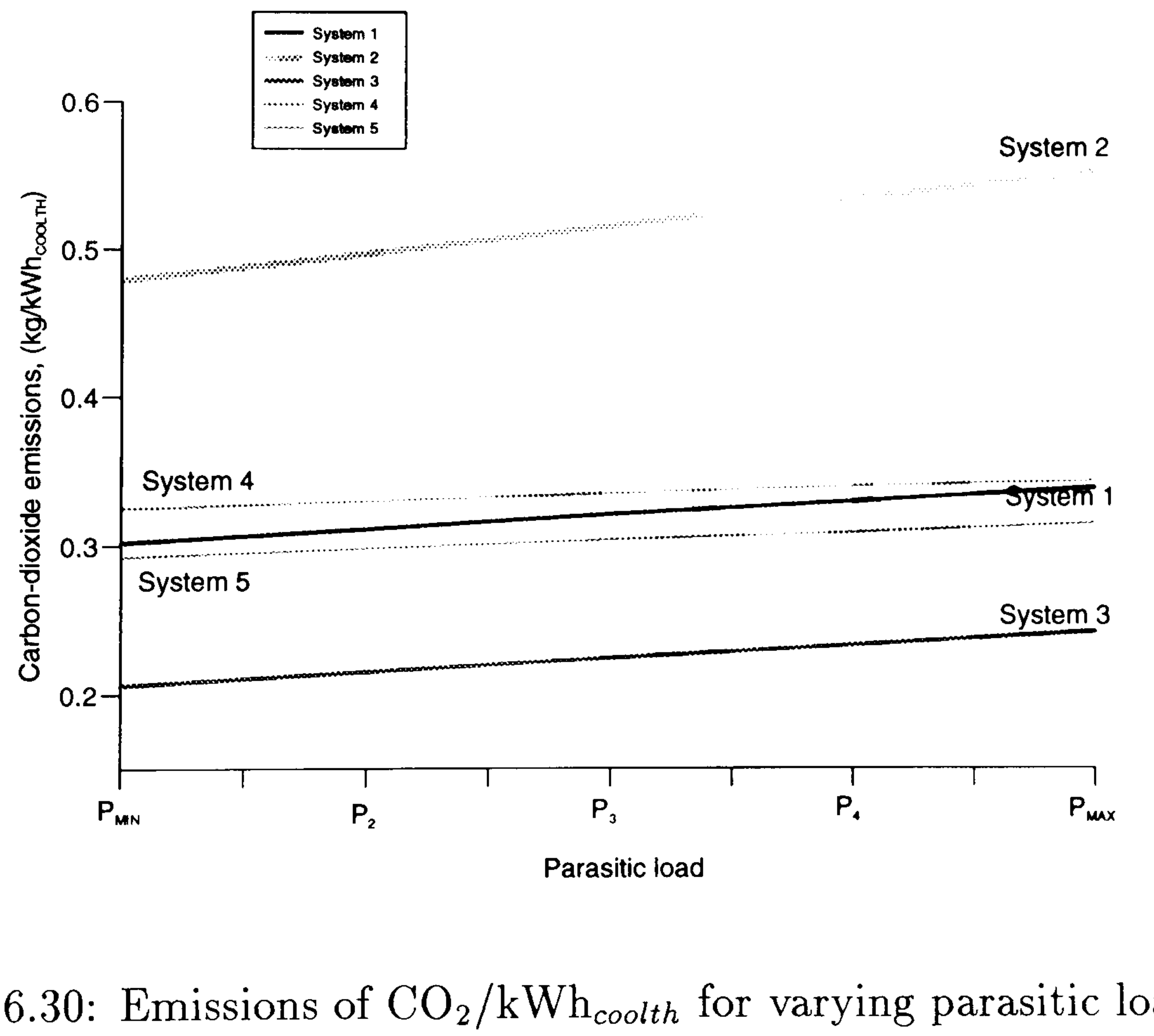


Figure 6.30: Emissions of CO_2/kWh_{coolth} for varying parasitic loads.

The parasitic load is increased linearly, which produces a similarly linear increase in the level of CO_2 emissions for each of the five systems. When the parasitic load is increased from P_{min} to P_{max} the advantage - in terms of lower CO_2 emissions - of System 3 over the two vapour-compressions remains approximately the same. System 1's advantage over System 4 decreases slightly as the parasitic load is increased, reaching parity at the upper end of the range.

6.5.3 Extending the CO_2 Emission Analysis to Include Variations of the Generator and Evaporator Temperatures

The levels of CO_2 emissions from the integrated CHP and absorption system have been determined for the specified operating conditions. The rates of CO_2 emissions will now be considered for varying CHP and absorption chiller's operating conditions. Once the cooling output of the absorption chiller has been determined for a set heat-input, the effect - on the CHP unit and absorption chiller - of changes in the temperature and mass-flow rate of the heat-source will be predicted.
The COP and/or cooling-output (capacity) of the integrated CHP and absorption system will vary with: The temperature of the CHP unit's hot-water; the mass-flow rate of the CHP unit's hot water; selected evaporator and chilled-water temperature; the cooling-water temperature; Li-Br-water solution concentration levels; ambient temperature and the temperature drop across the generator.

Variations in Hot-Water Temperature:
Effects on the Absorption system.

As the source water temperature is increased from 90 to 115 °C, the capacity of the absorption chiller increases approximately linearly - see Figure 6.31 and Tables 6.13 & Table E.1. The graph in Figure 6.31 indicates that the variation of the source-water temperature from the CHP unit will control the capacity of the absorption chiller. Tables 6.13 and E.1 show that the COP of the absorption chiller does not change significantly under these circumstances.

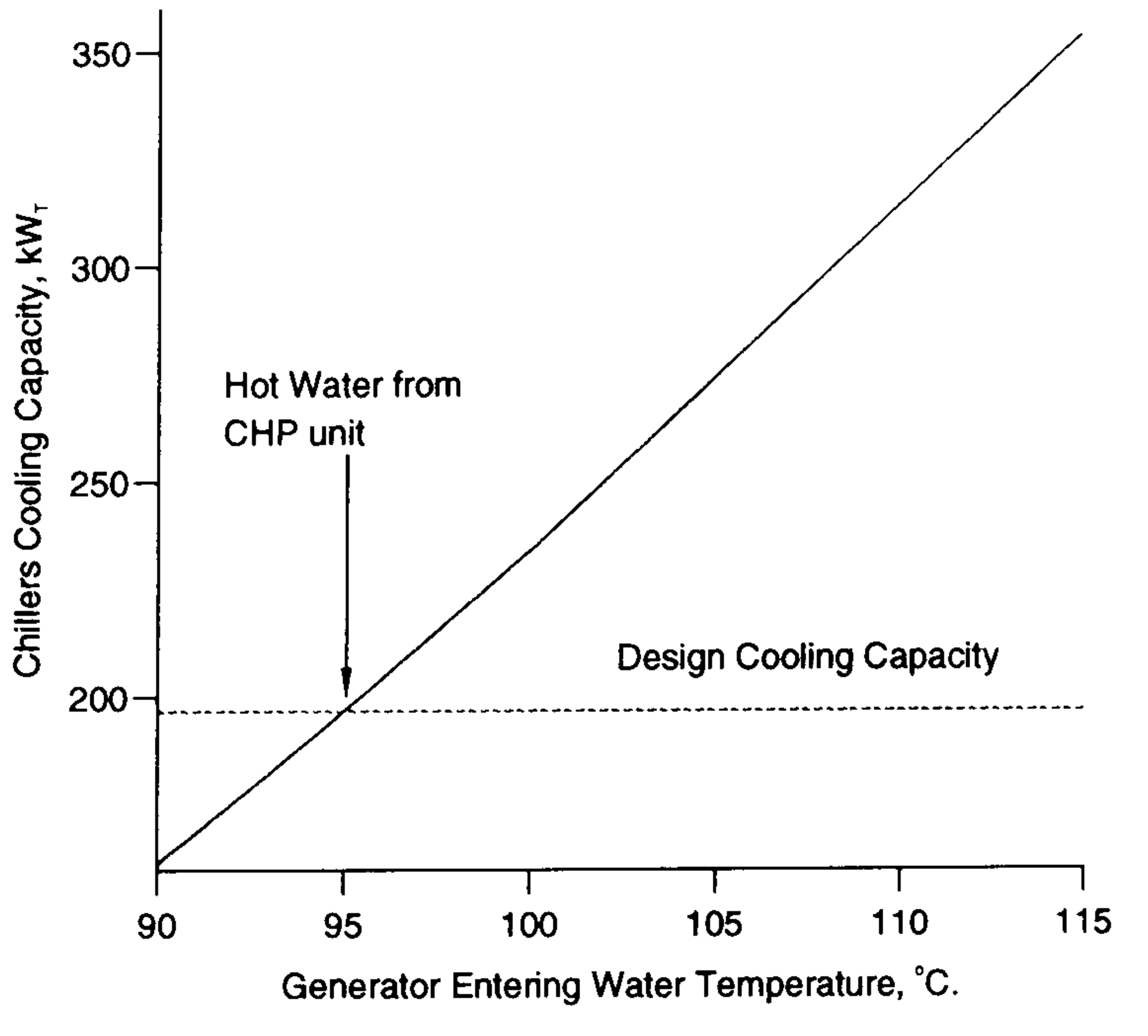


Figure 6.31: Variation of the absorption chiller's cooling capacity with generator temperature.

Over the range 90 to 115° C, the temperature of the water supplied to the generator increased by 28% so producing a 120% rise in capacity. This rise in capacity occurs because the increased heat supply to the generator causes more of the refrigerant to be boiled off from the solution. The result is an increase in the concentration of LiBr in the solution returning to the absorber, which in turn will cause more of the refrigerant to be absorbed by the solution in the absorber. Consequently the rate of evaporation of the refrigerant in the evaporator increases which will improve the cooling-effect (capacity) of the system.

	Generator Temperature						
Entry temperature, ^oC	90.0	91.0	93.0	95.0	97.0	100.0	115.0
Exit temperature, ^oC	85.8	86.6	88.3	90.0	91.7	94.2	106.3
Heat Energy input, kW	244	255.6	273.0	290	307.9	337	505.5
Cooling capacity, kW_{coolth}	161.6	168.5	182.5	196.8	211.4	233.8	354.1
COP	0.662	0.659	0.668	0.678	0.687	0.69	0.70

Table 6.13: Variation of cooling-capacity with source-water temperature to the generator.

Cooling-Water Temperature Variations

Another critical factor, which will affect the value of the COP of the absorption system, is the temperature of the cooling-water returning from either the cooling tower or cooling fans - see Figure 6.32 and Table 6.14 & Table E.2 in Appendix E. Figure 6.32 shows that as the temperature of the water entering the condenser decreases, the COP of the absorption chiller increases. The absorption chiller's capacity also increases as indicated in Table 6.14. The effect on CO_2 emissions due to variations in this factor have been predicted and are also found in the table.

The graph in Figure 6.32 shows the COP ranging from 0.65 to 0.73 against variations in cooling water temperature ranging from 26°C to 32°C. Over this temperature range (i.e. +23%), the CO_2 emissions will vary from approximately 0.22kg to 0.37kg per kWh_{coolth}, an increase of 68%.

System 1	Cooling-water temperature, ^oC			
	26	28	30	32
Capacity, kW_{coolth}	265	229	196	163
CO_2 emissions, kg per 22.4kWh_e & 38.9kWh_T, kg	14.75	14.75	14.75	14.75
CO_2 emissions for remaining CHP heat input, kg	13.1	13.1	13.1	13.1
CO_2 emissions for boiler heat input, kg	31.42	31.42	31.42	31.42
Total CO_2, kg	59.6	59.6	59.6	59.6
CO_2/unit, kg/kWh_{coolth}	0.22	0.26	0.30	0.37

Table 6.14: Rates of CO_2 emissions for varying cooling-water temperatures for CHP+absorption chiller+boiler system (minimum parasitic load).

Figure 6.33 presents the CO_2 emissions per kWh_{coolth} for each of the other four systems.

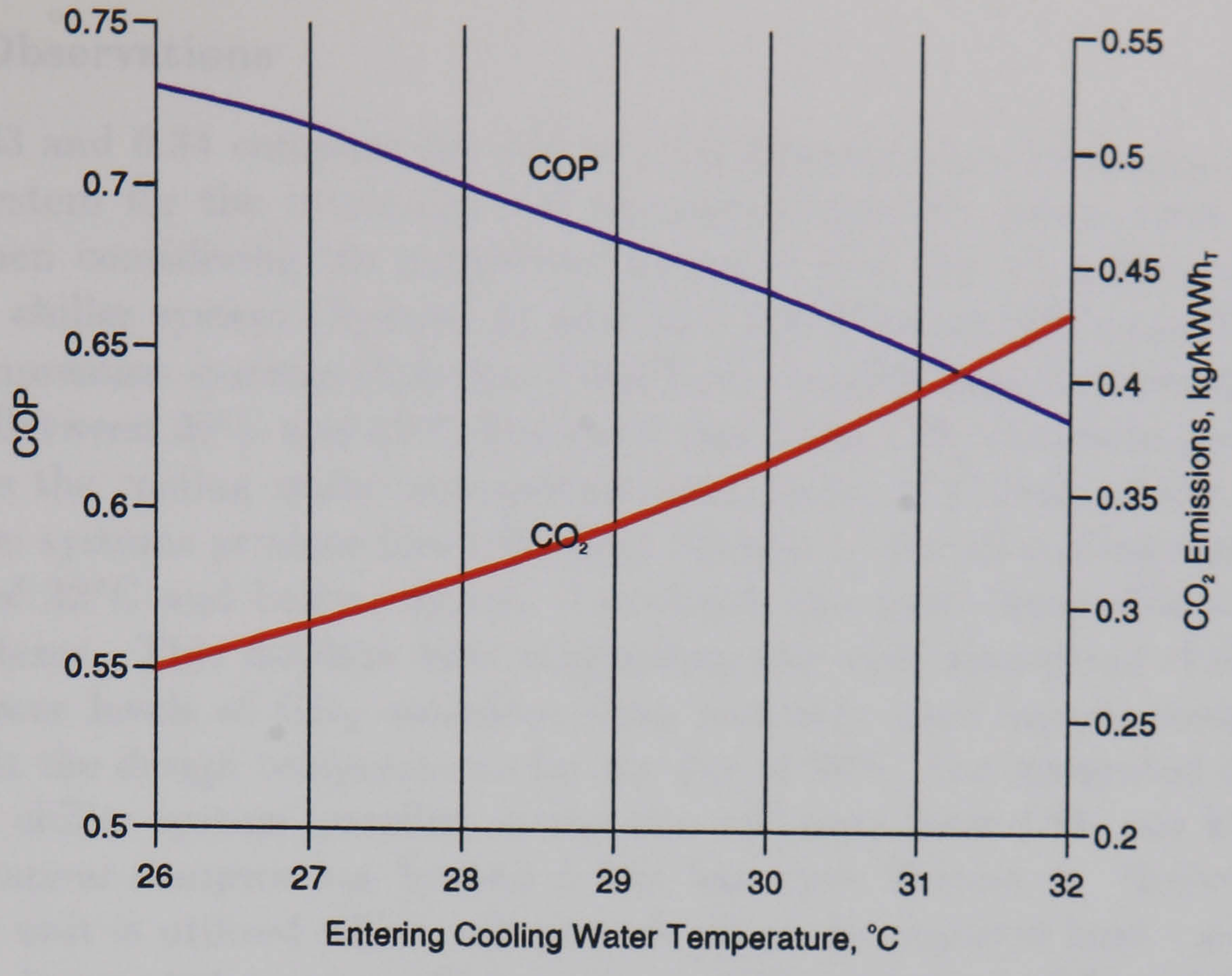


Figure 6.32: Variation of CO_2 emissions and COP with cooling-water's inlet temperature for the integrated CHP and absorption chiller system (System 1).

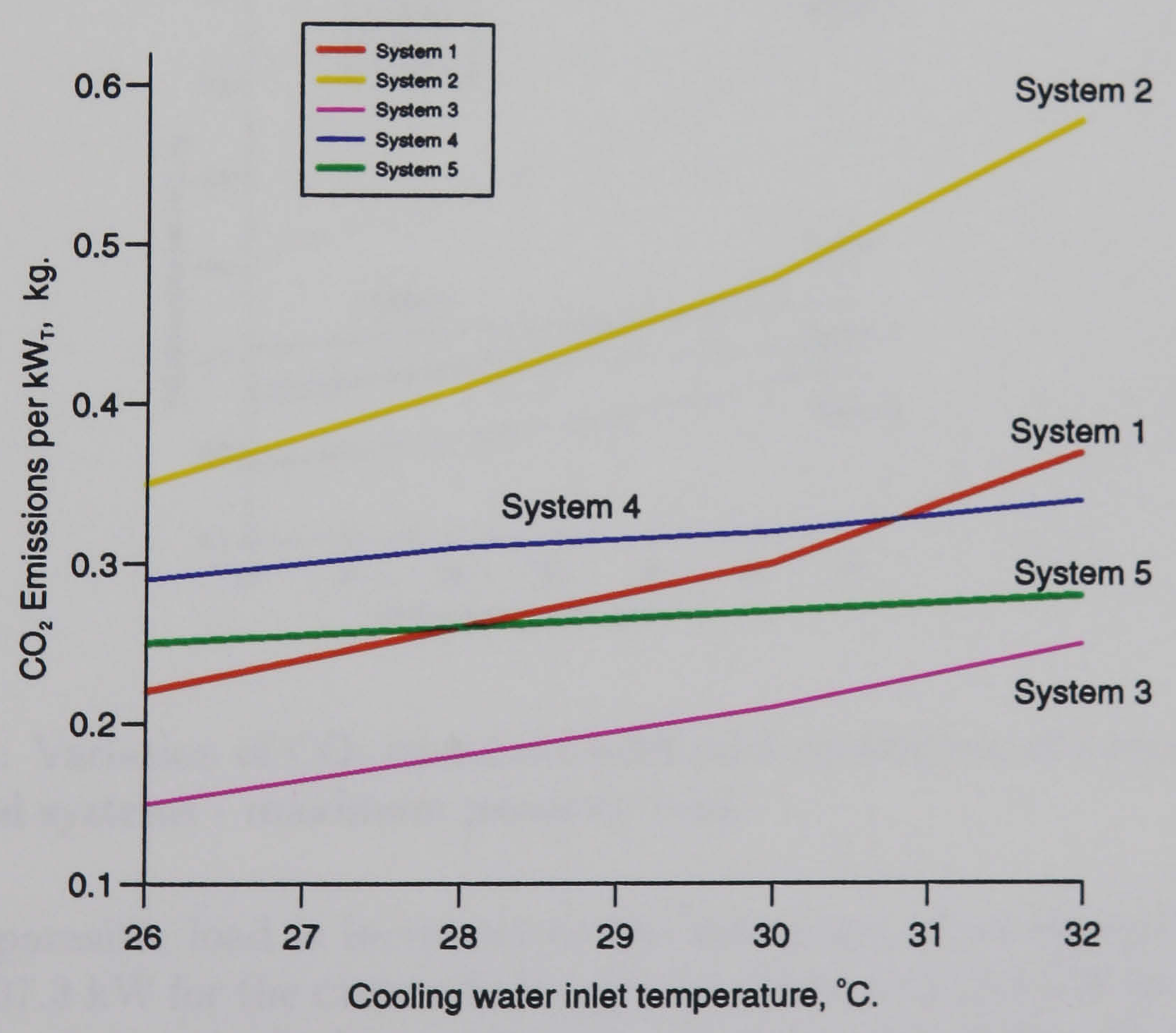


Figure 6.33: Variation of CO_2 emissions with inlet cooling-water's temperature for the specified systems (minimum parasitic load).

General Observations

Figures 6.33 and 6.34 compare the rate of CO_2 emissions per kWh_{coolth} achieved for each system for the minimum and maximum parasitic power loads respectively. When considering the mimimum parasitic load the integrated CHP and absorption chiller system (System 1) produces less CO_2 per kWh_{coolth} than the vapour-compression systems (Systems 4 and 5) for cooling-water temperatures below 28°C. Between 28°C and 31°C Systems 5 has lower CO_2 emissions per unit of cooling. As the cooling water temperature rises above 31°C both of the vapour-compression systems produce less CO_2 than System 1. For all cooling-water temperatures of 32°C and below, System 3 produces the most favourable results of all the systems. This displays how integrating CHP and absorption chillers can produce lower levels of CO_2 emissions than similarly sized vapour-compression systems. At the design temperatures for the site of 30°C, the integrated CHP and absorption chiller system installed at the site will emit more CO_2 per kWh_{coolth} than the vapour-compression System 5 but less than System 4. However, if a larger CHP unit is utilised which will provide all of the required heat - as in System 3, the integrated system will have lower CO_2 emissions. The combination of relatively high parasitic load, above 22.4kW, and inadequate heat output of the CHP unit presently installed at the site, that fulfils only 56% of the absorption chillers requirements, provide the the main explanation for the high CO_2 emissions compared to the vapour-compression systems.

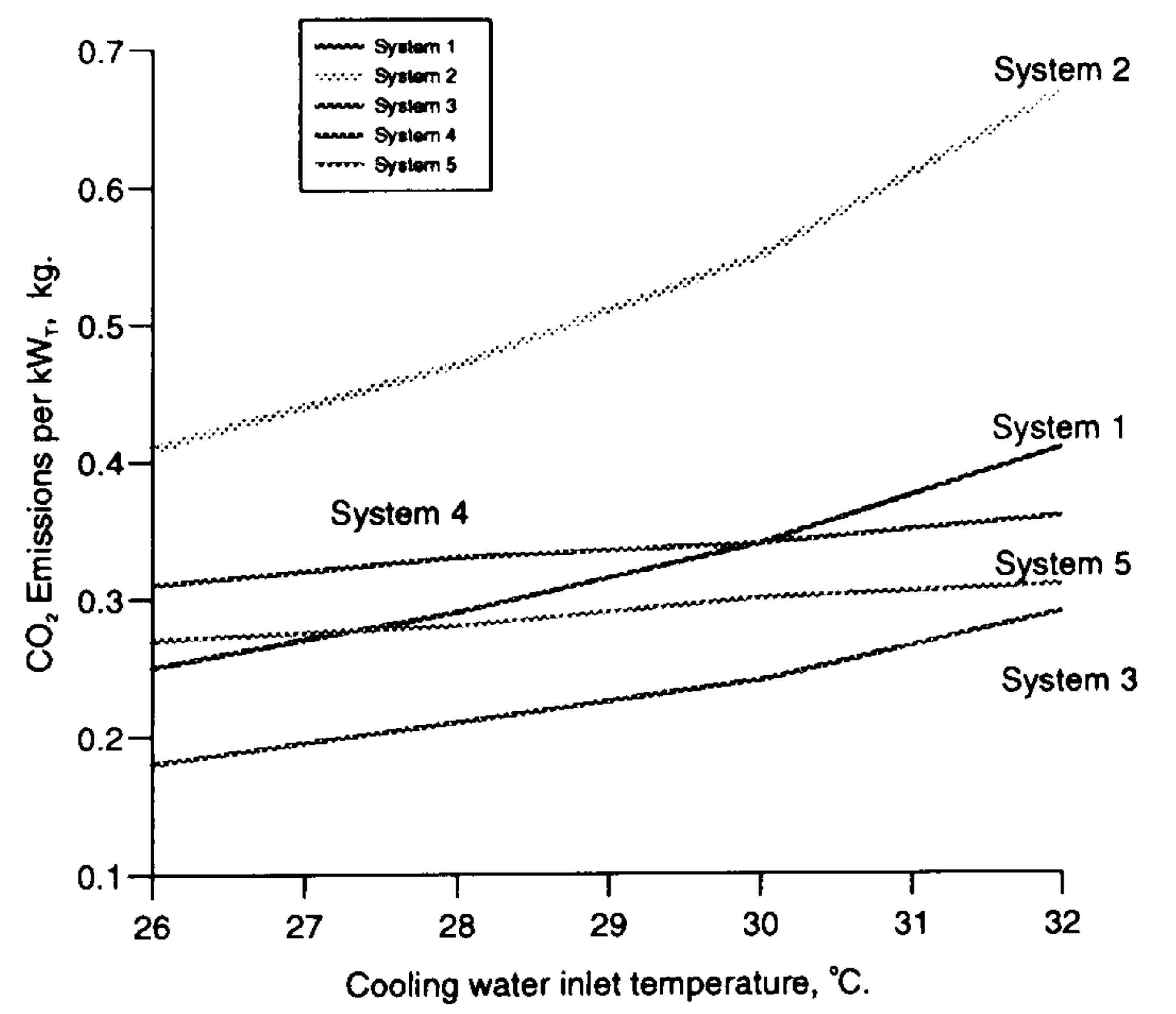


Figure 6.34: Variation of CO_2 emissions with inlet cooling-water's temperature for the specified systems - maximum parasitic load.

When the parasitic load is increased to the maximum of its potential operating range (i.e. 37.3 kW for the CHP and absorption system and 12.4 kW for the vapour-compressions systems), the large CHP unit and absorption chiller will maintain its advantage over the two VC systems for all temperatures in the range - see Figure 6.34. However, the advantage of the installed system at te site (i.e. System 1). will only exist for cooling water temperatures of below 30°C.

Other possible variations in the system which will have an effect but which will not be pursued in detail here are presented below.

Solution Concentration Levels

The concentration of the solution changes throughout the absorption cycle. Varying the heat input to the generator will result in the evaporation of either more or less of the refrigerant from solution. Consequently, the solution returning to the absorber will have changed in concentration. The amount of refrigerant in relation to the absorbent indicates the concentration level of the solution. As the solution becomes more concentrated, the potential for absorption of the refrigerant increases resulting in an increased refrigeration effect. Conversely, as the solution weakens the refrigeration effect will decrease.

Temperature Drop Across the Absorption chiller Unit.

The temperature drop across the generator is approximately 5°C. The capacity of the absorption chiller is controlled by means of the hot water mass-flow rate ($\dot{m}$) and the water temperature. Increasing the temperature of the source-water will result in a greater temperature drop across the chiller (for constant value of $\dot{m}$). The increased generator-temperature will raise the capacity of the absorption chiller.

The CHP unit was sized to operate under a set electrical power and heat output. If the temperature of the hot-water 'off' the engine (ie. after collecting heat from the oil and cooling water circuits and exhaust gases) is reduced, then the efficiency of operation of the unit will decrease. This is because the additional heat required to raise the water to the set operating-temperature is not utilised. Another inefficiency arises if the temperature of the returning water to the CHP unit is too high. This can occur as a result of the relatively small temperature drop across the absorption chiller leading to only part of the heat from the oil or engine circuits in the CHP unit transferring to the water. It is possible to avoid this eventuality by passing the returning water - from the absorption chiller to the CHP unit - through a heat-exchanger, which in turn can be used either to pre-heat feed-water to the boilers or to heat the water used in the tap systems. This will produce a reduced return-water temperature to the CHP unit providing an increase in the efficiency of the unit.

Future Work

The resources available for this study did not allow a comprehensive site survey, including long-term on-site monitoring of the CHP unit and absorption chiller system. The results presented indicate the displacement of CO_2 emissions, possible through the application of the integrated system. Future research should include a full on-site study, taking account of the daily heat, electricity and cooling delivered by the integrated CHP and absorption chiller system together with flow-rates and temperatures.

6.5.4 Conclusions

It has been found that for a chilled-water temperature of 6°C and cooling water temperature of 30°C required at the site, the installed CHP and absorption chiller (System 1) produce 0.30kg/kWh of CO_2 emissions whilst a similarly-sized vapour-compression chiller produced 0.29kg/kWh (System 5) or 0.32 (System 4) kg/kWh). Increasing the parasitic loads to each of the systems or reducing the assumed level of CO_2 emissions from centrally generated electricity will decrease any advantage achieved by the CHP and absorption chiller systems over the VC systems.

The performance of the integrated CHP and absorption chiller systems installed at the site was tested for varying source and cooling-water temperatures. The COP will vary significantly when the temperature of the cooling-water to the absorber and condenser varies. The system was tested for a range of different cooling-water inlet temperatures between 26 to 32°C. Over this range the COP decreased from 0.73 to 0.64 representing a fall over 12%, producing decreasing CO_2 emissions from 0.37kWh_{coolth} to 0.22 kg/kWh_{coolth} for the installed system. If the temperature of the cooling water into the condenser is reduced to 26°C, then the integrated system produces 0.22 kg versus 0.25 kg and 0.27 kg CO_2/kWh from the vapour-compression systems. This indicates that the integrated CHP and absorption chiller system can displace CO_2 emissions when compared to those for a similarly sized vapour-compression system.

If the size of the CHP unit installed at the site is increased so that it can supply all of the 294 kW of heat required by the absorption chiller as in System 3, then the integrated system will produce less CO_2 for all cooling-water temperatures of 32°C and below. At the design conditions, a 294 kW_T CHP unit will produce 0.21 compared with 0.27 and 0.32kg CO_2/kWh_{coolth} in the cases of the vapour-compression systems. This represents an improvement of 22% and 34% less CO_2 emissions respectively.

The parametric analysis has shown that the results are sensitive to several factors; the source and cooling-water temperatures together with the power consumption of the parasitic loads and the assumed CO_2 displacement rates for centrally generated electricity. It is not possible to make sweeping conclusions from these results because each system will have significantly different distribution arrangements.

Integrated CHP and absorption systems offer one solution to the combined problems of summer waste-heat utilisation and the need to displace the use of CFCs, HCFCs and HFCs, which are used in the operation of conventional electrically-driven vapour-compression chiller systems. However, the intermittent and peaky demands for cooling might call for the introduction of hybrid systems which incorporate cooling systems, which utilise both absorption and electric chillers in a central plant. These can offer flexibility by base loading the absorption chiller and using the electric chiller for peak demands.

6.6 Chapter Summary

The potential for integrating small-scale CHP and absorption chiller systems has been presented in three sections: (i) the introduction to absorption chilling and its application to small-scale CHP, (ii) a preliminary feasibility study for the installation of an integrated CHP and absorption chiller system at a local hospital and (iii) a comparative analysis of the carbon-dioxide emissions produced by electrically-driven chillers versus those produced by heat-driven absorption chillers.

The integrated small-scale CHP and single-stage absorption chiller system can be technically and economically viable if applied when there is sufficient energy demands for the energy produced by the CHP unit and when the cooling demand can be matched to the supply of heat from the CHP unit. The integration of the two technologies can significantly increase the environmental benefits, which arise on account of the application of CHP on its own. In addition to CO_2 - with its associated 'global warming potential' - displacement, the utilisation of absorption chillers displaces CFCs and to a lesser extent HCFCs, which have been associated with ozone depletion. Increased energy-efficiency and a switch from electrically-driven chillers to heat-driven absorption chillers are two of the main benefits offered by the integration of the two separate systems.

The cooling-load at the hospital was found to be inadequate, at present, to render cost-effective the introduction of a single-stage absorption chiller in combination with a small-scale CHP unit. This situation could change if capital grants become available for this type of system at the site or significant reductions in the capital cost of absorption chillers is achieved.

The CO_2 emissions, arising as a result of the production of air-conditioning by both types of systems have been assessed for a variety of operating conditions. CO_2 emissions per kWh_{coolth} were similar to those for the electrically-driven chiller at the site studied. If a larger CHP unit were to be installed - as opposed to the $165kW_T$ unit that supplies only 56% of the absorption chiller's heat requirement - which could satisfy all of the demand for heat from the absorption chiller, then the integrated system would displace 0.06 kg CO_2 at design conditions and up to 0.10 kg CO_2 per kWh_{coolth} produced representing a reduction of 22% and 40% respectively, when compared to the vapour-compression system. The results vary significantly depending on the assumptions made and the size and complexity of the pipe-distribution system determining the electrically-powered parasitic-load required. The change in CO_2 emissions per kWh_{coolth} was also studied for varying source-water and cooling-water temperatures. Increasing the temperature of the source-water supplied by the CHP unit from 90°C to 115°C leads to an increase in the chiller's capacity of 120% but has little effect on the COP. The effect of changing cooling-water temperatures can impact directly on capacity and COP, which can result in greater CO_2 displacements for reducing cooling-water temperatures. If the temperature of the cooling-water is reduced to 30, 28 or 26°C for system 1, then up to 12% more CO_2 could be displaced relative to the emissions from the best vapour-compression system. With a larger CHP unit installed, satisfying all of the heat requirements of the absorption chiller, then this advantage could be increased to up to 34%.

Chapter 7

Summary, General Conclusions and Proposals for Future Work

The technical, economic, environmental and strategic market potential for small-scale CHP and the application of three different CHP systems has been presented in this thesis. Chapter 2 gave an overview of the UK electricity industry with the emphasis placed on the determination of the factors, which are crucial for the continuing expansion of the UK's CHP industry and market. The future for CHP is inextricably tied to the future of the electricity industry as a whole. Three predictions (i.e. scenarios) for the development of the electricity industry over the next two decades, which would have direct effects on the CHP sector, were identified. New empirical data were presented to predict potential developments of the industry in a management-orientated analysis. It seems likely that several elements from each of the three scenarios presented will evolve. The three scenarios are: (i) New and reduced CO_2 limits set by the Climate Control Conference + stricter environmental legislation, (ii) Changes to the Pool mechanism for pricing electricity, and (iii) Business as usual. The overall future for CHP if scenarios 1 and 3 result is positive with a strong emphasis on energy-efficiency, reform of the role of the regulator, the increase of the Government-set target for installed CHP capacity (10 GW by 2010 and 13GW by 2017), the implementation of a carbon-based tax and the removal of restrictive (anti-CHP) legislation. The realisation of scenario 2 will put strong downward pressure on electricity prices, which in isolation will adversely effect the economics of CHP systems. Respondants to the questionnaire put the following factors as most significant for the continuing growth of the CHP market:

1. Higher unit electricity-prices.

2. A reduction in the capital costs of CHP units.

3. A more open market for the import or export of electricity.

4. Government backing and incentives for the CHP industry.

5. Considered equal fifth - Cheaper gas prices and the removal of any remaining 'unfair' regulatory, licensing or legislative barriers for CHP within the electricity industry.

Another benefit will occur if the correct apportioning of emissions for each method of energy production is applied, levelling the 'playing field' for energy producers. Significantly, the future for CHP requires a supportive Government. If this technology is left only to the peculiarities of market forces, generally the lowest cost and quickest-return options will be selected without any concern for the long-term and wider environmental effects.

The technical and market breakdown of CHP in the UK was presented in Chapter 3, as background reading for the the subsequent chapters. Chapters 4, 5 and 6 documented research into the technical, economic and environmental potential for the application of three separate types of CHP systems. A case-study specific approach was undertaken. This allowed the viability of the systems to be tested on new applications. In each of the systems presented, an attempt was made to utilise more of the heat and power - produced by the small-scale CHP units - thus increasing the economic and environmental benefits occurring through the adoption of CHP units. By offering a small-scale system that utilises more of the heat and electricity produced by the CHP units, it is possible to increase the number of potential applications for CHP. The remaining part of this chapter will seek to summarise these predicted benefits, achieved as a result of the implementation each system.

The investigation of the potential for adopting two smaller sized CHP units (the two-unit system), in place of a single larger unit (the single-unit system), in order to gain operational and economic benefits was described in Chapter 4. The installation and operation of two CHP units together is not unique. This study investigated the potential for the application of the system to five different case-studies. A new predictive model was developed to simulate the behaviour of the two-unit system when installed at the five separate case-studies and compared the results with those for the single-unit system. For one of the case studies considered, it is possible to achieve shorter pay-back periods when using the double-unit rather than the single-unit system. The 507+255 kW_e CHP installation at the hospital leads to a one-month shorter pay-back period being achieved than that for the single-unit system for an availability of 95%. In the other two cases (where CHP is considered as a viable economic option), longer pay-back periods ensue by the installation of the two-unit rather than the single-unit system. However, a shorter pay-back period is only achieved because an availability of 95% is considered for the two-unit system against 90% for the single-unit system. The operation of the two-unit system at the leisure complex illustrated how energy-utilisation can be increased to above that of the single CHP unit. However, the system is still not economically viable in this case. Pay-back periods are reduced further when allowances are made for maintenance cost reductions, the export of surplus electricity and the extended life-expectancy of the secondary CHP unit, although the single unit remains the most economically attractive in all cases except that of the hospital.

The possibility of achieving a significantly shorter pay-back period would be a great incentive for any potential investor in CHP. However, the predictions made indicate that this is not possible for the majority of the cases considered. It is possible that many of the other benefits of the two-unit system suggested could also influence favourably the investor. For example, the availability of the second unit for back-up in the case of breakdown or servicing of the other unit could be a major consideration, if security of supply is essential. In these cases, the value of the secondary CHP unit could be significant to a company because of the high cost of a complete shut-down or shortfall of electricity and heat at a site. The two-unit system can offer increased protection from this expensive eventuality.

Several emerging issues, which appear to limit the number of useful applications of CHP have been identified and studied in this thesis. The daily mismatch between the demand for electricity and the thermal load supplied is one of the main issues. For large-scale CHP, it has been widely documented that applying thermal-energy storage to CHP systems can decouple the generation of electricity from the production of thermal energy. The second of the technical systems examines the potential for the integration of a thermal-energy storage unit and small-scale CHP. The potential for the system is predicted for the five case-studies used in Chapter 4 with the aid of a newly developed simulation model. Following an extensive search, an operational example of the proposed system was located. This allowed an original study of a working integrated system and provides information concerning the economic and environmental savings achieved through its installation and operation. This study of small-scale CHP found that the potential for the utilisation of thermal-energy-storage does not exist at the stated sites. The study of the viability of integrating TES and CHP systems to five different test-cases, highlighted several important restrictions. The first and most significant of these concerned the sizing methodology employed for the selection of small-scale CHP units. It is usual to size the unit on the average base thermal-load to ensure near constant operation (i.e. giving maximum operating efficiency) and the shortest pay-back period. The second hurdle is the high level of capital and installation costs required for the TES system. The relatively-low economic value attached to heat provides a further obstacle for the quick return of capital for an investment in the integrated system. Finally, the availability of low priced off-peak electricity at the majority of potential sites, limits the daily operation - on economic grounds - of the CHP unit to 17 hours. This limitation excludes the possibility of generating and storing heat during these off-peak hours for use at peak times.

The scale of the quantity of heat available for storage and the quality (temperature) of this heat, illustrates the significant difference between small-scale and large-scale systems. For a typical small-scale unit in the range used for this study, the heat output will lie between 100 kW and 1 MW. With the pre-mentioned sizing-methodology employed, it is likely that at times of low heat demand (i.e.

mid-afternoon in the summer), the demand for heat may be at a minimum, representing only approximately 50% of the CHP unit's potential heat output. The heat-storage potential would then lie between 50 and 500 kWh, which is equivalent in value to 50 pence and £5 per hour (assuming no losses). Assuming that this demand and supply pattern repeated itself for 8 hours per day and 3 months of the year the savings might be worth between £370 and £3,700 per annum. It is apparent that the larger units can provide greater potential for heat storage than the smaller units, and clearly have more significant savings, and consequently, quicker returns on their investments. Unfortunately, for the application of TES to small-scale CHP units, especially at the lower end of the specified CHP size range, the capital, installation and running costs are disproportionally high and lead to longer pay-back periods. Additionally, heat losses are proportionally higher for the smaller systems.

A new & original study of an integrated small-scale CHP and absorption chiller system - documented in Chapter 6 - publicised several crucial criteria for the successful and beneficial application of these types of systems. The case-study investigated represents only one operational example of these types of systems in the UK and is presented as the first documented case of its environmental performance, in terms of its CO_2 displacement potential.

The potential for integrating small-scale CHP and absorption-chiller systems has been presented in three broad sections: (i) the introduction to absorption chilling and its application to small-scale Combined Heat-and-Power, (ii) a preliminary appraisal of the feasibility of installing a CHP unit combined with an absorption-chiller at a local hospital and (iii) a comparative analysis of the carbon-dioxide emissions produced by electrically-driven chillers versus those produced by heat-driven absorption-chillers.

It has been demonstrated that the integrated small-scale CHP and single-stage absorption-chiller system can be technically and economically viable if applied when there is sufficient energy demands for the heat (of suitable temperature) and electricity produced by the CHP unit and when the cooling demand can be matched to the supply of heat from the CHP unit. The integration of the two technologies can significantly increase the environmental benefits, which arise on account of the application of CHP on its own. In addition to CO_2 - with its associated 'global warming potential' - displacement, the utilisation of absorption-chillers displaces CFCs and to a lesser extent HCFCs, which are used in vapour-compression systems and have been associated with ozone depletion. Increased energy-efficiency and a switch from electrically-driven chillers to heat-driven absorption-chillers are two of the main benefits offered by the integration of the two separate systems.

The cooling-load at the hospital studied, was found to be inadequate at present and therefore, the introduction of a single-stage absorption-chiller in combination with a small-scale CHP unit would not be cost-effective. This situation could change if capital grants become available for this type of system at this site or significant reductions in the capital cost of absorption-chillers is achieved.

The CO_2 emissions, which arise as a result of the production of air-conditioning by both types of systems have been assessed for a variety of operating conditions. It was found that for the site studied in Section 6.3 (with specific design requirements), that the level of CO_2 emissions per kWh_{coolth} were similar to those for the electrically-driven chiller. If a larger CHP unit were to be installed satisfying all of the demand for heat from the absorption-chiller, the integrated system would displace 0.06 kg CO_2 per kWh_{coolth} at design conditions and up to 0.10 kg CO_2 per kWh_{coolth} produced, representing a reduction of 22% and 40% respectively, when compared to the vapour-compression system. The results vary significantly depending on the assumptions made and the size and complexity of the pipe-distribution system determining the electrically-powered parasitic-load required for each case. The change in CO_2 emissions/kWh_{coolth} was also studied for varying source-water and cooling-water temperatures. With only a small increase in COP for increasing generator temperature, it was also found that the reduction in CO_2 emissions was slight at approximately 0.02 kg for the rise in temperature from 90 to 115°C. The effect of changing cooling-water temperatures can impact directly on capacity and COP, which can result in greater CO_2 displacements for reducing cooling-water temperatures. If the temperature of the cooling-water is reduced to 30, 28 or 26°C for system 1, then up to 12% more CO_2 could be displaced relative to the emissions from the best vapour-compression system.

7.1 General Conclusions & Implications

CHP is a proven & highly energy-efficient means of energy production. The technical research presented in this thesis has examined systems seeking to extend the range of potential applications for the technology - on an energy-utilisation and CO_2 displacement basis. The selection, sizing, maintenance and installation of CHP systems must be undertaken with a great deal of care and attention to detail. Therefore, it is vital to determine the patterns of current and future energy use for a potential application as well as relying on historical data. This methodology will also apply to the integration of TES and absorption chillers with CHP systems, as it is important to examine each new application for the technologies separately. Otherwise, the additional efficiencies achieved through the application of CHP might be wasted, leading to negative publicity for the technology in general. The additional benefits offered by the use of absorption chillers, namely, the displacement of CO_2 emissions and the elimination CFCs, are important promotional assets in today's environmentally conscious world. However, whilst these systems can increase energy-utilisation, reduce CO_2 emissions and the use of CFCs, they are not usually economically viable (in the current market conditions) without financial subsidy. This point introduces the essential part played by governmental bodies for the future prosperity of both CHP on its own and in tandem with other technologies. In order to achieve the wider benefits, which can potentially be attained through the adoption of these systems, a helping hand is required to overcome current free-market obstacles and pressures.

One significant obstacle is the volatility of energy prices in the UK. The market unit prices for gas and electricity over the last five years have varied significantly. The economic viability of CHP requires that a positive and consistent differential is maintained between these two commodities. One of the main points from the survey undertaken in Chapter 2 indicated that high electricity prices were essential for CHP prosperity. The constant variation of utility prices has resulted in continually changing pay-back periods for CHP projects, making predictions uncertain and leading to a lack of confidence in the systems economic viability as a whole. Government backing is essential to overcome obstacles and ensure the future prosperity of CHP in the UK. The form of support given in the past and throughout Europe has usually been to offset the capital cost with a grant or tax-break. In parts of Europe, the installation of CHP is strongly supported by individual governments and is promoted with capital grants of up to 50%. The previous government of the UK recently offered £1 million for the promotion of CHP by way of capital grants of up to 25% of total capital cost. This was welcomed but rapidly consumed. A significant disadvantage of the capital grant system is that it supports only the purchase of the CHP unit and does not guarantee the continued use of the systems - which may lie under-utilised or even unused if the market conditions encourage it. A more appropriate approach would be to encourage the purchase and use of CHP systems by giving the grant in the form of rebates for the use of CHP produced energy. The new problem will then be in terms of verification only. However, with CHP plant installed on-site, it will be easy to determine exact electrical use and a theoretical maximum for heat consumption. With this mechanism in place, it would then be straight-forward to apply varying levels of support to this energy-efficient and environmentally-friendly technology.

7.2 Proposals for Future Work

The structure of the new research in this thesis has been divided into four broad sections: (i) the non-technical research, namely - the study of the potential for CHP within the electricity industry - and three technical sections (ii to iv). It is appropriate that this section on future work is divided up in the same manner.

(i) The study undertaken in Chapter 2 examined the electricity and CHP sectors in detail. A new management approach has been adopted wherever possible, utilising tools such as S.T.E.E.P. analysis, the five forces model and scenario planning. In order to extend the research one step further and to introduce an increased measure of objectivity the views of industry experts were solicited via a survey. The results of this survey were useful to this study, providing a degree of objectivity. The limitation of the work concerned the sample size, which was limited to 14 with a response rate of approximately 60%. Future work should seek to increase the size of the sample and widened the sample of experts to include more CHP users. Additionally it would be beneficial to incorporate new questions which examine the scope for CHP from the end-users point of view.

(ii) The study undertaken in Chapter 4 of the potential benefits, which can be achieved through the use of two smaller CHP units in place of one single larger unit indicated that there was little prospect for economic benefit. However, the findings highlighted a number of potential secondary benefits of the application of the system. Future research should seek to determine the actual significance of these benefits to future and existing users.

(iii) The application of integrated small-scale CHP and TES systems is limited by the factors already documented. An exception whereby small-scale integrated CHP/TES systems appear more valuable - on an energy and economic basis - is in their application to greenhouses. These systems can have the added advantage of the recovery and the use in greenhouses of the CO_2 in the exhaust gases; the CO_2 being used for enhanced growth rates in the crop. This is one area which provides interesting potential. TES allows heat stored during the day to be used after dark to heat the greenhouses. Initial savings appear promising, but a full documentation of a system as a case study will be necessary to verify the expected benefits.

(iv) The resources available for the study undertaken in Chapter 6 did not allow a comprehensive survey - including long-term on-site monitoring - of the CHP and absorption-chiller system. The results presented indicate - given the declared assumptions - the likely displacement of CO_2 emissions, which are possible through the application of the system. Future research should include the full on-site study, taking account of the daily heat, electricity and cooling delivered by the integrated CHP and absorption-chiller system together with flow-rates and temperatures. Such a comprehensive study will require the allocation of substantial resources. At the time of writing, it is understood that ETSU are about to undertake a full appraisal of the system. It will be interesting to compare the results from this chapter with the results from the full ETSU study upon completion.

QUESTIONS: DICTATING THE HYPOTHESIS	**RESULT METHODOLOGY**	**RESULTS**	**CONCLUSIONS**
WILL TWO CHP UNITS IN PLACE OF ONE PRODUCE SIGNIFICANT BENEFITS?	(1) Develop a predictive model (2) Test on cases. (3) Validate	(1) One sites produced shorter pay-back periods. (2) More heat and power was produced. (3) Secondary benefits included: increased availability	A number of significant benefits were indicated. However, high capital costs present obstacles
CAN THE UTILISATION OF ENERGY STORAGE BENEFIT SMALL-SCALE CHP SYSTEMS?	(1) Research Energy Storage. (2) Develop a model. & Test on cases (3) Research specific case-study	An integrated system is feasible but is limited by: (1) CHP sizing methodology, (2) capital and installation costs, (3) low economic value of heat (4) the availability of low-cost off-peak electricity	Energy and CO_2 saved, however savings are insufficient to provide a pay-back period of an acceptable length.
CAN ABSORPTION CHILLERS PROVIDE SIGNIFICANT CO_2 SAVINGS?	(1) Research Absorption systems (2) Develop a predictive model. & Test on hospital case-study. (3) Examine CO_2 displacement potential	(1) Technically feasible with several installations (2) Important: Source & cooling water temperatures. (3) Application to a local hospital proved uneconomic (4) Can displace more CO_2 than similarly sized VC systems.	The application of absorption chillers to small-scale CHP saves energy & displaces CO_2 emissions. However, without financial incentives the pay-back period is unacceptably long
DETERMINE THE FUTURE FOR CHP IN THE UK ESI UP TO THE YEAR 2017?	Develop & study three scenarios: (1) Increased pollution control, (2) Changes the Pool pricing sys. (3) Business as usual.	The CHP market will benefit if scenarios 1 & 3 are realised and will not if scenario 2 is. Factors vital for CHP's market success. (i) Higher electricity prices, capital costs reduced etc.	Scenarios 1 & 3 favour CHP. CHP requires that electricity prices are maintained at a certain level & that the true cost of pollution is included for each method of energy production. CHP requires government support.

Table 7.1: Summary of the four research questions and results

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Appendix A

S.T.E.E.P. Analysis

S.T.E.E.P. Analysis

Social

- Trend towards self generation - back to basics.
- A move away from electricity as the main energy for domestic appliances.
- More information and education concerning energy-efficiency leading to a more discerning consumer when it comes to purchasing energy-efficient appliances.
- Growing concerns about energy production/consumption and the associated effects on the environment, especially concern about the links between pollution and health.
- NIMBY
- Population demography.
- Lifestyle changes.
- Pressure from consumer and lobby groups

Technological

- Fuel cells
- More solar or renewable power sources.
- Nuclear fusion.
- More efficient transmission of electricity across long distances.

- Development of a viable micro-scale CHP system for the domestic market.
- Seven Barrier constructed.

Economic

- The relative pricing of electricity versus other fuel sources will have a significant effect on the demand patterns for electricity.
- Higher gas prices.
- Volatility of electricity prices
- Higher coal or oil prices
- Acceptance of longer pay-back periods for capital projects.
- Variation of interest rates

Environmental

- Climate changes as a result of global warming leading to less electricity use.
- Concern continues to grow over the high levels of polluting gases being emitted as a direct consequence of electrical power production.
- Pressure to phase out nuclear power.

Political

- Government stability
- Foreign trade regulations.
- The introduction of a carbon tax.
- New power stations will only be considered if the comply with certain thermal characteristics (i.e. CHP).
- Geographical restrictions on power stations.
- Phasing out of Nuclear power stations
- Global conflict that restricts the supply of fuels
- Change of government from Conservative to Labour in 1997.

- Increased enforcement of environmental legislation
- Dwindling gas supplies leading ti increased imports of gas from Holland and Norway.
- Energy import restrictions.
- Change to the franchise market in April 1998.
- Taxation policy (e.g. a carbon based tax)
- EU CHP policy gaining strength as a result of an agreement by EU energy Ministers in 1996 to open up electricity markets to competition [104].

Appendix B

Questionnaire and Results.

Energy Industry & CHP Questionnaire

For this study you are asked to answer 24 questions concerning the UK electricity supply and CHP industries? In each case, your opinions are sought as to how much you either agree or disagree with the relevant statement. This is an anonymous study and you can remain assured that all information will be treated in the strictest confidence. Thank you for your assistance.

		Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
		1	2	3	4	5
1	More examples of the sucessful application of CHP are required to help encourage the growth of the market further.	☐	☐	☐	☐	☐
2	Changes to the franchise market in AD 1998 will lead to a reduction of electricity unit-prices for domestic customers.	☐	☐	☐	☐	☐
3	The Government of the UK could provide a significant stimulus to the CHP industry via grants or tax incentives.	☐	☐	☐	☐	☐
4	Stricter environmental legislation emerging (in the form of lower limits for the pollutants emitted from power generating stations) from the EU will benefit CHP.	☐	☐	☐	☐	☐
5	The introduction of carbon, toxic or noxious emissions taxes will not lead to a larger market for CHP.	☐	☐	☐	☐	☐
6	For the CHP market to be increased above $5MW_e$, technological developments, which enable the utilisation of more of the waste heat from the CHP units need to occur.	☐	☐	☐	☐	☐
7	15% of the UK's electricity can realistically be produced by CHP by AD 2010.	☐	☐	☐	☐	☐
8	A change to a Labour Government will not favour CHP.	☐	☐	☐	☐	☐
9	Further Tax or grant incentives are necessary to encourage CHP uptake.	☐	☐	☐	☐	☐
10	Cost savings to the customer for heat and/or electricity determine the rate of CHP uptake.	☐	☐	☐	☐	☐

	Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
	1	2	3	4	5
11 The environmental benefits locally of CHP are not a significant enough incentive for the potential CHP investor.	☐	☐	☐	☐	☐
12 It would be more effective to concentrate resources on achieving the introduction of a few large-scale CHP installations rather than many small-scale ones.	☐	☐	☐	☐	☐
13 CHP reliability is no longer a major concern for the CHP investor or energy consumer.	☐	☐	☐	☐	☐
14 If a cleaner and more efficient means for producing electricity from large coal-fired stations is developed, CHP investments will suffer.	☐	☐	☐	☐	☐
15 The fragmentation CHP industry in the UK does not help customer confidence in the technology.	☐	☐	☐	☐	☐
16 The reduced level of overall emissions produced by CHP will be its biggest selling point in future.	☐	☐	☐	☐	☐
17 A shortfall in the total supply of electricity within the UK in the future will lead to an increased demand for CHP installations.	☐	☐	☐	☐	☐
18 The acceptance of long pay-back periods for large-scale electricity generation plant will become less acceptable.	☐	☐	☐	☐	☐
19 The development of CHP plus ancillary equipment, eg. thermal energy storage, absorption chillers etc., will widen the market for CHP.	☐	☐	☐	☐	☐
20 Carbon dioxide reduction policies will be beneficial for the CHP industry.	☐	☐	☐	☐	☐

21 Please study the factors 1-10 below and indicate by giving a grade of 1-5 (1 indicates greatest importance and 5 least important) for every statement which you consider are important for the the continued development of CHP in the UK:

	1	2	3	4	5
Higher electricity prices.	☐	☐	☐	☐	☐
Cheaper unit gas prices.	☐	☐	☐	☐	☐
A reduction in the capital costs of CHP units.	☐	☐	☐	☐	☐
Government backing and incentives for the CHP industry.	☐	☐	☐	☐	☐
Increased penalties for pollution.	☐	☐	☐	☐	☐
Investment in the research and development of CHP technology.	☐	☐	☐	☐	☐
Greater advertising of the benefits arising from the installation of CHP.	☐	☐	☐	☐	☐
Acceptance of the 5 year pay-back period as the upper limit for financial investments.	☐	☐	☐	☐	☐
A more open market for the import/export of electricity.	☐	☐	☐	☐	☐
The removal of any remaining 'unfair' regulatory, licensing or legislative barriers for CHP within the electricity industry.	☐	☐	☐	☐	☐
The continuation of the Non Fossil-Fuel Levy, with CHP receiving a share the proceeds in relation to its contribution towards the reduction of carbon-dioxide emissions from energy production.	☐	☐	☐	☐	☐

22 Consider the seven scenarios (a) to (g) listed below. Please indicate for each scenario if you think i) It is likely and by how much and ii) the effect on the CHP industry if this scenario was to come about. Please score 0 to 5, where 0 indicates no effect or likelihood etc. and 5 indicates maximum effect or likelihood.

		Likelihood	Effect
(a)	Change to a Labour Government in the UK	....	....
(b)	Changes to the pool which will enable large consumers of power to negotiate directly with the generators	....	....
(c)	Stricter environmental legislation from Europe	....	....
(d)	The changes to the electricity franchise market in 1998	....	....
(e)	New and increased CO_2 limits are set following the next climate control conference	....	....
(f)	The development of a clean and abundant alternative fuel source	....	....
(g)	Unlimited international trade in electricity	....	....

		YES	NO
23	Are there any questions which you think should have been asked, but were not included in this survey?	☐	☐

If yes please state the question below.

....
....
....

24 What, in your opinion, are the three key factors which will influence the future for CHP and why?

(i)	....	(i)	....
(ii)	....	(ii)	....
(iii)	....	(iii)	....

Any other comments on CHP, the electricity industry or this questionnaire.

....
....
....
....

Energy Industry & CHP Questionnaire Results

The complete questionnaire given out to industry experts is included (in its original form) in appendix 2B of this thesis. The Sixteen questionnaires were sent out between December 1996 and March 1997. Eight replies were received between December 1996 and May 1997. Consequently some of the replies arrived after the general election. Twenty-two questions were selected and answered. The results were as follows.

	Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
	1	2	3	4	5
Question 1 1 More examples of the sucessful application of CHP are required to help encourage the growth of the market further.	☐	25%	☐	37.5%	37.5%

75% of the respondents agreed with Q1.

	Strongly Disagree	Disagree	Neither	Agree	Strongly Agree
	1	2	3	4	5
Question 2 2 Changes to the franchise market in AD 1998 will lead to a reduction of electricity unit-prices for domestic customers.	☐	25%	25%	50%	☐

No respondent had a strong opinion in answer to the statement in Q2. However, 50% indicated that they agreed with the statement.

Question 3

3 The Government of the UK could provide a significant stimulus to the CHP industry via grants or tax incentives.

1	2	3	4	5
			75%	25%

It was strongly felt that the government could assist CHP.

Question 4

4 Stricter environmental legislation emerging (in the form of lower limits for the pollutants emitted from power generating stations) from the EC will benefit CHP.

1	2	3	4	5
	37.5%	12.5%	37.5%	12.5%

Responses on this statement proved to be inconclusive.

Question 5

5 The introduction of carbon, toxic or noxious emissions taxes will not lead to a larger market for CHP.

1	2	3	4	5
	37.5%	37.5%	25%	

Result inconclusive.

Question 6

6 For the CHP market to be increased above $5MW_e$, technological developments, which enable the utilisation of more of the waste heat from the CHP units need to occur

1	2	3	4	5
12.5%	25%	25%	25%	12.5%

Result inconclusive.

Question 7

7 15% of the UK's electricity can realistically be produced by CHP by AD 2010.

1	2	3	4	5
12.5%		25%	50%	12.5%

The majority of respondents agreed with Q7.

Question 8

8 A change to a Labour Government will not favour CHP.

1	2	3	4	5
	37.5%	62.5%		

Result - No effect?

Question 9

9 Further Tax or grant incentives are necessary to encourage CHP uptake.

1	2	3	4	5
	12.5%	12.5%	62.5%	12.5%

75% of respondents agree with the statement in Q9.

Question 10

10 Cost savings to the customer for heat and/or electricity determine the rate of CHP uptake.

1	2	3	4	5
			62.5%	37.5%

Result - cost savings are considered vital for the increased uptake of CHP.

Question 11

11 The environmental benefits locally of CHP are not a significant

1	2	3	4	5
	12.5%		62.5%	25%

Result inconclusive.

Question 12

12 It would be more effective to concentrate resources on achieving the introduction of a few large-scale CHP installations rather than many small-scale ones.

1	2	3	4	5
25%	25%	12.5%	37.5%	

Result - 50% disagreed with this statement.

Question 13

13 CHP reliability is no longer a major concern for the CHP investor or energy consumer.

1	2	3	4	5
	62.5%	25%	12.5%	

Result - 62.5% disagreed with this statement, meaning reliability is still an important issue.

Question 14

14 If a cleaner and more efficient means for producing electricity from large coal-fired stations is developed, CHP investments will suffer.

1	2	3	4	5
	62.5%	25%	12.5%	

Result - 62.5% disagreed with this statement.

Question 15

15 The fragmentation CHP industry in the UK does not help customer confidence in the technology.

1	2	3	4	5
12.5%	12.5%	37.5%	37.5%	

Result inconclusive.

Question 16

16 The reduced level of overall emissions produced by CHP will be its biggest selling point in future.

1	2	3	4	5
12.5%	25%	50%	12.5%	

Result inconclusive.

Question 17

17 A shortfall in the total supply of electricity within the UK in the future will lead to an increased demand for CHP installations.

1	2	3	4	5
25%	37.5%		37.5%	

Result inconclusive.

Question 18

18 The acceptance of long pay-back periods for large-scale electricity generation plant will become less acceptable.

1	2	3	4	5
		50%	50%	

Result 50% felt that long pay-back periods would become less acceptable.

Question 19

19 The development of CHP plus ancillary equipment, eg. thermal energy storage, absorption chillers etc., will widen the market for CHP.

1	2	3	4	5
	12.5%		75%	12.5%

Result - 87.5% agreed with this statement, ie. the addition of ancillary equipment will widen the market for CHP.

Question 20

20 Carbon dioxide reduction policies will be beneficial for the CHP industry.

1	2	3	4	5
	12.5%	12.5%	37.5%	37.5%

Result - 75% agreed with this statement, that CO_2 reduction policies will benefit CHP.

Question 21.

21 Please study the factors 1-10 below and indicate by giving a grade of 1-5 (1 indicates greatest importance and 5 least important) for every statement which you consider are important for the the continued development of CHP in the UK:

	1	2	3	4	5	Average
Higher electricity prices.	87.5%	12.5%				1.125
Cheaper unit gas prices.	25%	25%	25%	12.5%	12.5%	2.625
A reduction in the capital costs of CHP units.	12.5%	62.5%	12.5%	12.5%		2.25
Government backing and incentives for the CHP industry.	25%	25%	25%	25%		2.5
Increased penalties for pollution.	12.5%	12.5%	50%	25%		2.875
Investment in the research and development of CHP technology.			50%	37.5%	12.5%	3.625
Greater advertising of the benefits arising from the installation of CHP.		12.5%	50%	25%	12.5%	3.375
Acceptance of the 5 year payback period as the upper limit for financial investments.		37.5%	12.5%	12.5%	37.5%	3.50
A more open market for the import/export of electricity.	25%	25%	37.5%	12.5%		2.375
The removal of any remaining 'unfair' regulatory, licensing or legislative barriers for CHP within the electricity industry.		62.5%	25%		12.5%	2.625
The continuation of the Non Fossil-Fuel Levy, with CHP receiving a share the proceeds in relation to its contribution towards the reduction of carbon-dioxide emissions from energy production.		50%	37.5%		12.5%	2.75

Analysis of the replies to question 21

Each of the questions has been given a weighted average, which is a function of the graded replies given to each statement by the respondent. The six statements which were considered the most important and of greatest significant to the development and expansion of the CHP industry were:

1. Higher electricity prices.
2. A reduction in the capital costs of CHP units.
3. A more open market for the import/export of electricity.
4. Government backing and incentives for the CHP industry.
5. JOINTLY - Cheaper gas prices and the removal of any remaining 'unfair' regulatory, licensing or legislative barriers for CHP within the electricity industry.

The three statements which were considered the least important and less significant to the development and expansion of the CHP industry were:

1. Investment in the research and development of CHP technology.
2. Acceptance of the 5 year pay-back period as the upper limit for financial investments.
3. Greater advertising of the benefits arising from the installation of CHP

Question 22

22 Consider the seven scenarios (a) to (g) listed below. Please indicate for each scenario if you think i) It is likely and by how much and ii) the effect on the CHP industry if this scenario was to come about. Please score 0 to 5, where 0 indicates no effect or likelihood etc. and 5 indicates maximum effect or likelihood.

		Response Average Likelihood	Response Average Effect
(a)	Change to a Labour Government in the UK	3.5	1.6
(b)	Changes to the pool which will enable large consumers of power to negotiate directly with the generators	3.0	2.75
(c)	Stricter environmental legislation from Europe	3.8	4.0
(d)	The changes to the electricity franchise market in 1998	3.5	2.5
(e)	New and increased CO_2 limits are set following the next climate control conference	2.7	3.75
(f)	The development of a clean and abundant alternative fuel source	1.7	3.6
(g)	Unlimited international trade in electricity	1.6	2.0

Question 24

Respondent 1.

Liberalisation of electricity markets in UK/Europe.
Will lead to lower electricity prices and lower returns on CHP plants.
1998' and the opening up of the franchise market.
Will facilitate the sale of electricity from CHP.
Introduction of stringent environmental legislation
Will kill" small CHP technology/market.

Respondent 2.

Energy prices.
CHP depends on savings to repay capital costs.
Government support.
A beneficiary of CHP is the government which, at present does not pay for it.
Technological development.
Including a trim economic small (less than 50kW) CHP package to pick up the space heating market.

Respondent 3.

Legislation.
Power vs. gas prices.
Technology improvements - reliability.

Respondent 4.

Unit gas price.
Unit electricity prices.
Environmental issues.

Respondent 5.

Capital cost pay-back time.
The unit is only purchased to provide savings over a long period.
Performance guarantees.
Provides insurance for end user to collect savings over time.

Respondent 6.

Electricity prices.
Sensitivity of savings to electricity/gas price.
General environment, legislation / government incentives.
Importance of a greener future.

Respondent 7.

Electricity costs.

Gas costs.

Pay-back.

Respondent 8.

Favourable energy prices.

Pay-back is very sensitive to energy prices.

Stable energy prices (it will never happen!).

Consumers are reluctant to invest when energy prices fluctuate wildly.

Economic incentives.

In the Netherlands where the government supports CHP there is huge capacity.

Appendix C

Heat-storage data for the five case studies.

	OFF PEAK STORAGE				PEAK STORAGE			
MONTH	HEAT FROM CHP UNIT (kWh)	HEAT DEM BY SITE (kWh)	HEAT AVAIL FOR STORE (kWh)	VALUE OF HEAT SAVED pounds	HEAT AVAIL FOR STORE (kWh)	HEAT SHORT FALL DAY (kWh)	MAX HEAT STORE DAY (kWh)	VALUE OF HEAT SAVED pounds
JAN	798.0	523.0	684.0	241.2	0.0	3480.0	0.0	0.0
FEB	798.0	488.0	684.0	217.8	0.0	3187.0	0.0	0.0
MAR	798.0	466.0	684.0	241.2	0.0	3055.0	0.0	0.0
APR	798.0	328.0	684.0	233.4	0.0	1620.0	0.0	0.0
MAY	798.0	267.0	684.0	241.2	0.0	1111.0	0.0	0.0
JUN	798.0	221.0	684.0	233.4	94.0	491.0	94.0	32.1
JUL	798.0	156.0	684.0	241.2	292.0	140.0	140.0	49.4
AUG	798.0	131.0	684.0	241.2	528.0	51.0	51.0	18.0
SEP	798.0	195.0	684.0	233.4	163.0	302.0	163.0	55.6
OCT	798.0	268.0	684.0	241.2	5.0	979.0	5.0	1.8
NOV	798.0	303.0	684.0	233.4	0.0	1168.0	0.0	0.0
DEC	798.0	385.0	684.0	241.2	0.0	1952.0	0.0	0.0
SITE 1 Electrical output of CHP unit 70. Heat output 114.								
Value of offpeak stored heat (pounds) 2229. cost of fuel 5449.0								
Value of peak stored heat (pounds) 157.								

Table C.1: Heat storage data for the hotel.

	OFF PEAK STORAGE				PEAK STORAGE			
MONTH MONTH	HEAT FROM CHP UNIT (kWh)	HEAT DEM BY SITE (kWh)	HEAT AVAIL FOR STORE (kWh)	VALUE OF HEAT SAVED pounds	HEAT AVAIL FOR STORE (kWh)	HEAT SHORT FALL DAY (kWh)	MAX HEAT STORE DAY (kWh)	VALUE OF HEAT SAVED pounds
JAN	5096.0	24280.0	0.0	0.0	0.0	91352.0	0.0	0.0
FEB	5096.0	21330.0	0.0	0.0	0.0	77388.0	0.0	0.0
MAR	5096.0	19169.0	0.0	0.0	0.0	68876.0	0.0	0.0
APR	5096.0	16713.0	0.0	0.0	0.0	57271.0	0.0	0.0
MAY	5096.0	16052.0	0.0	0.0	0.0	51435.0	0.0	0.0
JUN	5096.0	14418.0	0.0	0.0	0.0	48714.0	0.0	0.0
JUL	5096.0	15590.0	0.0	0.0	0.0	53641.0	0.0	0.0
AUG	5096.0	18498.0	0.0	0.0	0.0	65785.0	0.0	0.0
SEP	5096.0	19968.0	0.0	0.0	0.0	71861.0	0.0	0.0
OCT	5096.0	22094.0	0.0	0.0	0.0	82055.0	0.0	0.0
NOV	5096.0	29309.0	0.0	0.0	0.0	111110.0	0.0	0.0
DEC	5096.0	22875.0	0.0	0.0	0.0	83959.0	0.0	0.0

SITE 2 Electrical output of CHP unit 507. Heat output 728.

Value of offpeak stored heat (pounds) 0. cost of fuel 38840.8
Value of peak stored heat (pounds) 0.

Table C.2: Heat storage data for the hospital.

	OFF PEAK STORAGE				PEAK STORAGE			
MONTH MONTH	HEAT FROM CHP UNIT (kWh)	HEAT DEM BY SITE (kWh)	HEAT AVAIL FOR STORE (kWh)	VALUE OF HEAT SAVED pounds	HEAT AVAIL FOR STORE (kWh)	HEAT SHORT FALL DAY (kWh)	MAX HEAT STORE DAY (kWh)	VALUE OF HEAT SAVED pounds
JAN	2268.0	3780.0	0.0	0.0	0.0	3672.0	0.0	0.0
FEB	2268.0	6188.0	0.0	0.0	0.0	9520.0	0.0	0.0
MAR	2268.0	5026.0	0.0	0.0	0.0	6698.0	0.0	0.0
APR	2268.0	3514.0	0.0	0.0	0.0	3026.0	0.0	0.0
MAY	2268.0	3934.0	0.0	0.0	0.0	4046.0	0.0	0.0
JUN	2268.0	2485.0	0.0	0.0	0.0	527.0	0.0	0.0
JUL	2268.0	1197.0	1071.0	377.6	2601.0	0.0	0.0	0.0
AUG	2268.0	1302.0	966.0	340.6	2346.0	0.0	0.0	0.0
SEP	2268.0	1645.0	623.0	212.6	1513.0	0.0	0.0	0.0
OCT	2268.0	2660.0	0.0	0.0	0.0	952.0	0.0	0.0
NOV	2268.0	3640.0	0.0	0.0	0.0	3332.0	0.0	0.0
DEC	2268.0	3619.0	0.0	0.0	0.0	3281.0	0.0	0.0

SITE 3 Electrical output of CHP unit 200. Heat output 324.

Value of offpeak stored heat (pounds) 0. cost of fuel 14581.6
Value of peak stored heat (pounds) 0.

Table C.3: Heat storage data for the leisure complex.

	OFF PEAK STORAGE				PEAK STORAGE			
MONTH MONTH	HEAT FROM CHP UNIT (kWh)	HEAT DEM BY SITE (kWh)	HEAT AVAIL FOR STORE (kWh)	VALUE OF HEAT SAVED pounds	HEAT AVAIL FOR STORE (kWh)	HEAT SHORT FALL DAY (kWh)	MAX HEAT STORE DAY (kWh)	VALUE OF HEAT SAVED pounds
JAN	630.0	864.0	336.0	118.5	0.0	3983.0	0.0	0.0
FEB	630.0	882.0	336.0	107.0	0.0	4114.0	0.0	0.0
MAR	630.0	720.0	348.0	122.7	0.0	2906.0	0.0	0.0
APR	630.0	472.0	372.0	126.9	8.0	1098.0	8.0	2.7
MAY	630.0	341.0	396.0	139.6	76.0	377.0	76.0	26.8
JUN	630.0	340.0	396.0	135.1	70.0	372.0	70.0	23.9
JUL	630.0	332.0	396.0	139.6	64.0	374.0	64.0	22.6
AUG	630.0	336.0	396.0	139.6	67.0	370.0	67.0	23.6
SEP	630.0	340.0	396.0	135.1	75.0	375.0	75.0	25.6
OCT	630.0	345.0	396.0	139.6	79.0	375.0	79.0	27.9
NOV	630.0	481.0	372.0	126.9	11.0	1053.0	11.0	3.8
DEC	630.0	776.0	342.0	120.6	0.0	3211.0	0.0	0.0

SITE 4 Electrical output of CHP unit 48. Heat output 90.

Value of offpeak stored heat (pounds) 1505. cost of fuel 3727.1
Value of peak stored heat (pounds) 157.

Table C.4: Heat storage data for the flats.

	OFF PEAK STORAGE				PEAK STORAGE			
MONTH MONTH	HEAT FROM CHP UNIT (kWh)	HEAT DEM BY SITE (kWh)	HEAT AVAIL FOR STORE (kWh)	VALUE OF HEAT SAVED pounds	HEAT AVAIL FOR STORE (kWh)	HEAT SHORT FALL DAY (kWh)	MAX HEAT STORE DAY (kWh)	VALUE OF HEAT SAVED pounds
JAN	2898.0	0.0	2898.0	1021.9	3726.0	12168.0	3726.0	1313.8
FEB	2898.0	0.0	2898.0	923.0	3726.0	12048.0	3726.0	1186.7
MAR	2898.0	0.0	2898.0	1021.9	3726.0	12168.0	3726.0	1313.8
APR	2898.0	0.0	2898.0	988.9	3726.0	11024.0	3726.0	1271.4
MAY	2898.0	0.0	2898.0	1021.9	3726.0	8944.0	3726.0	1313.8
JUN	2898.0	0.0	2898.0	988.9	3726.0	9352.0	3726.0	1271.4
JUL	2898.0	0.0	2898.0	1021.9	3726.0	8944.0	3726.0	1313.8
AUG	2898.0	0.0	2898.0	1021.9	3726.0	8944.0	3726.0	1313.8
SEP	2898.0	0.0	2898.0	988.9	3726.0	11024.0	3726.0	1271.4
OCT	2898.0	0.0	2898.0	1021.9	3726.0	12168.0	3726.0	1313.8
NOV	2898.0	0.0	2898.0	988.9	3726.0	12688.0	3726.0	1271.4
DEC	2898.0	0.0	2898.0	1021.9	3726.0	10560.0	3726.0	1313.8

SITE 5 Electrical output of CHP unit 255. Heat output 414.

Value of offpeak stored heat (pounds) 12031. cost of fuel 18613.9
Value of peak stored heat (pounds) 15469.

Table C.5: Heat storage data for the industrial building.

Appendix D

Additional data for the operational small-scale integrated CHP/TES system.

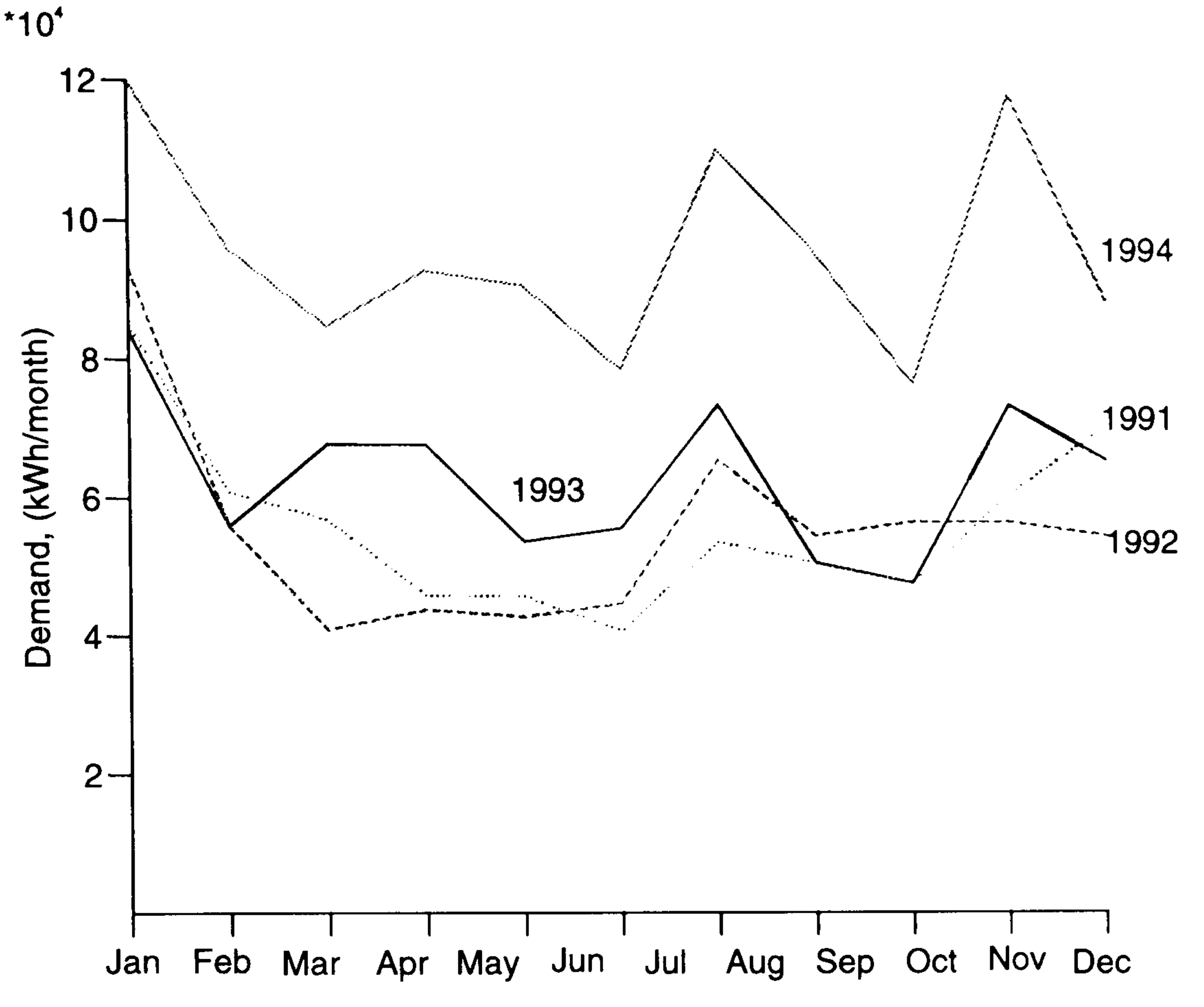

Figure D.1: Manufacturing site's electicity demand: 1992 to 1994.

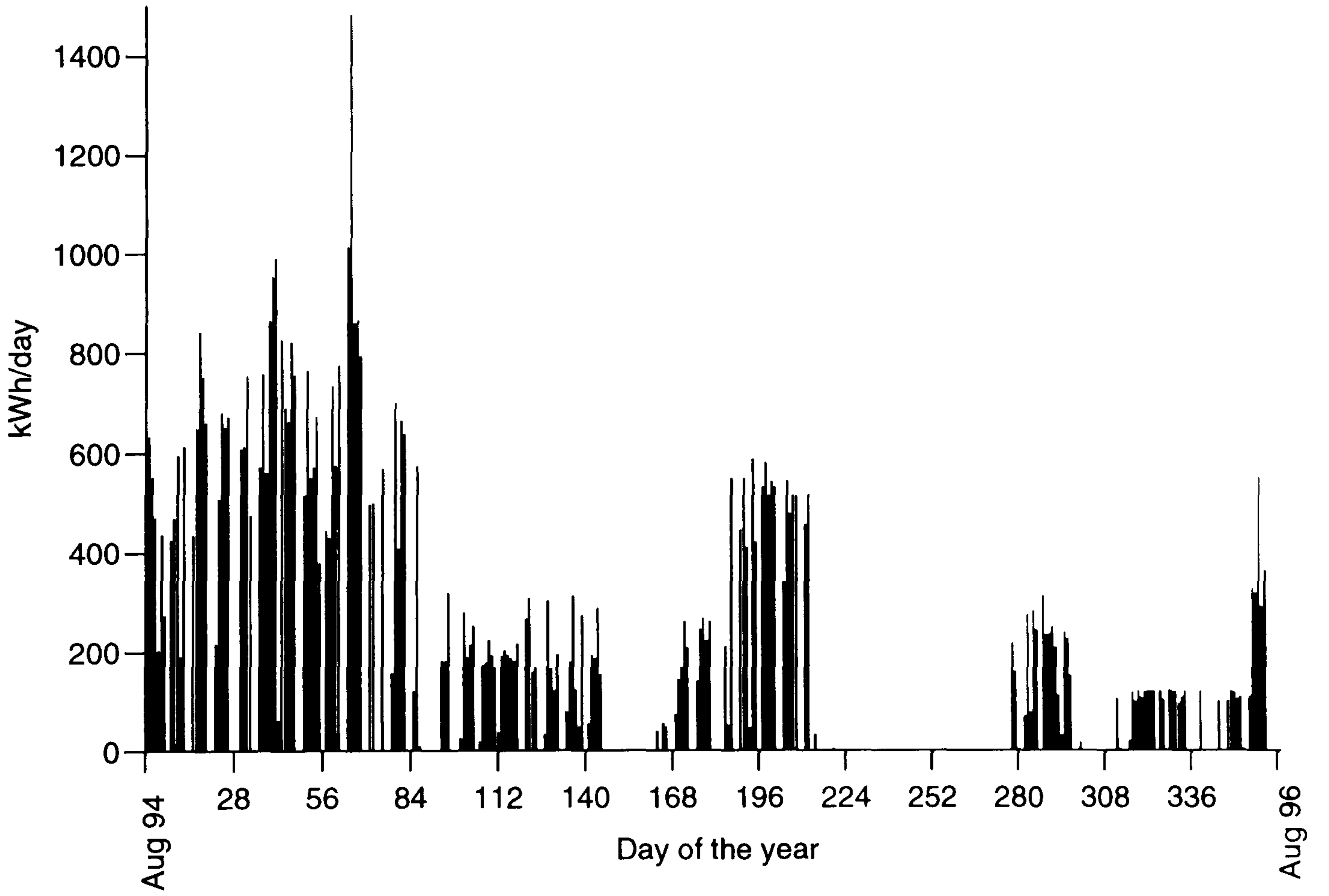

Figure D.2: CHP daily electricity output at the manufacturing site: 1994/95.

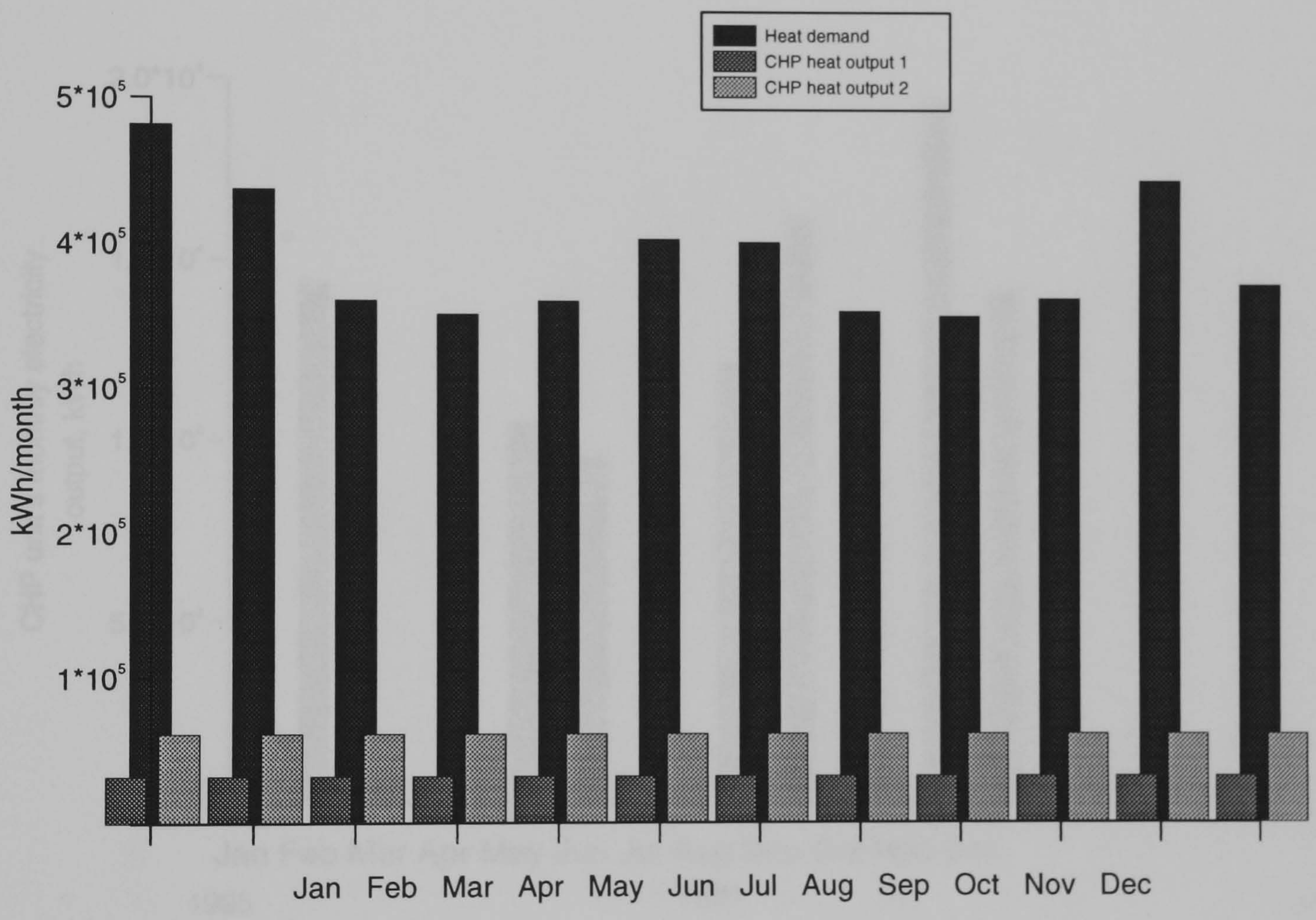

Figure D.3: Heat demand and CHP output at the maunfacturing site.

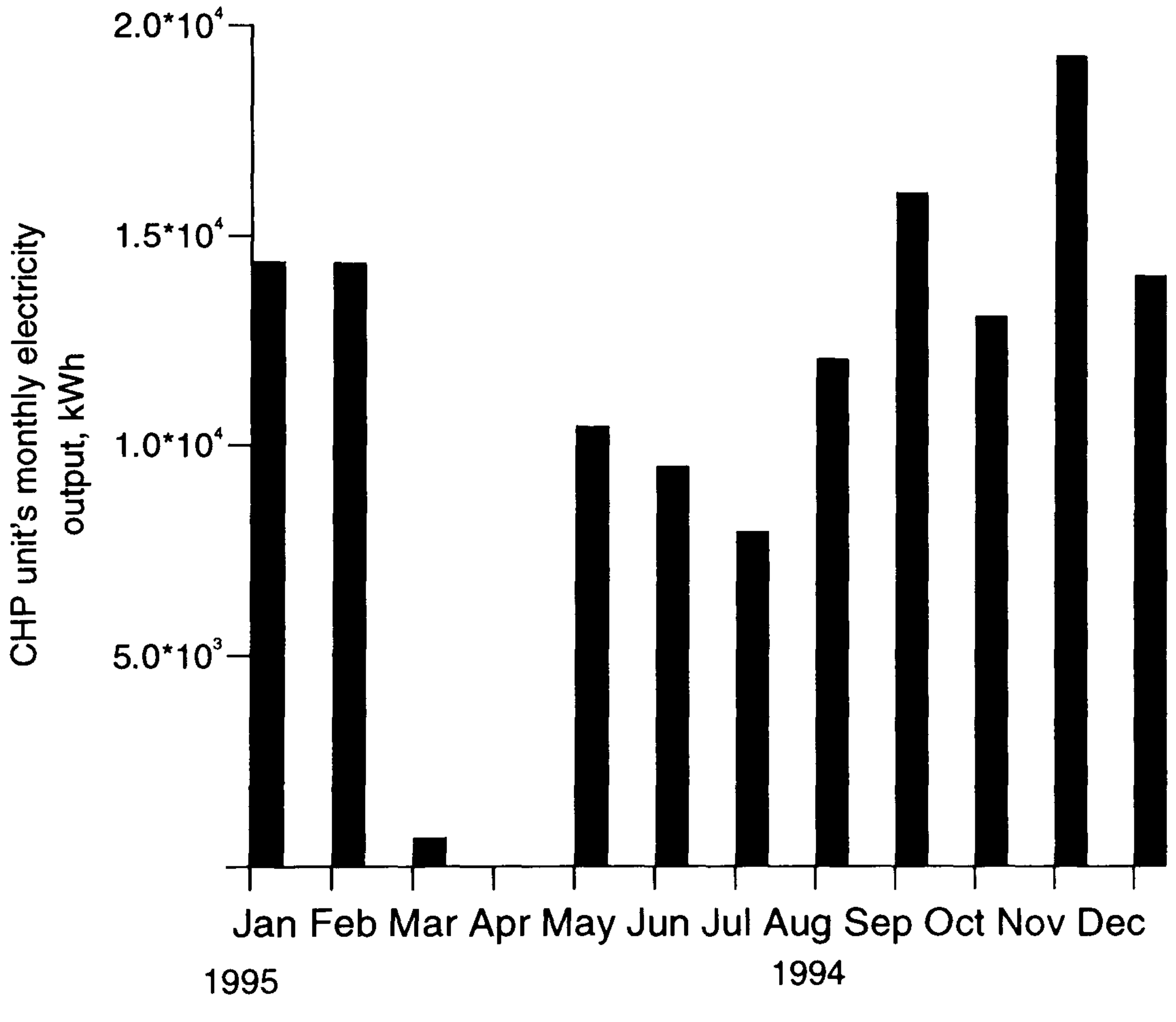

Figure D.4: Monthly electricity output from the CHP unit at the manufacturing site.

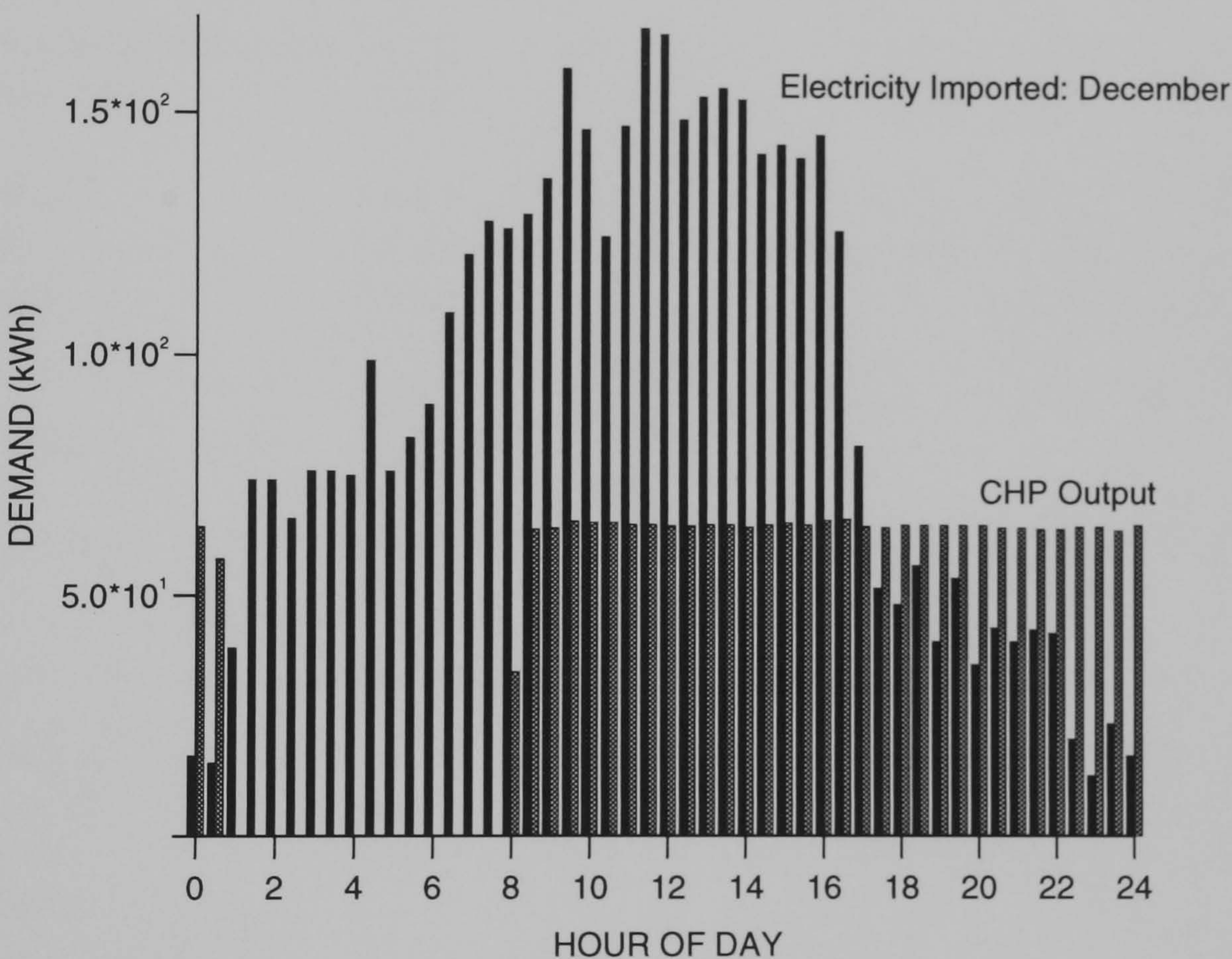

Figure D.5: Daily electricity demand and output from the CHP unit at the manufacturing site.

Appendix E

Absorption chiller specifications.

Unit size	16JB012						
Evaporator pass	2	2	2	2	2	2	2
Generator pass	2	2	2	2	2	2	2
Volts (50 Hz)Hertz	400	400	400	400	400	400	400
Cooling, kW	161.6	168.5	182.5	196.8	211.4	233.8	354.1
Evaporator Fluid	FW	FW	FW	FW	FW	FW	FW
Entering Temp, C	11	11	11	11	11	11	11
Leaving temp, C	6	6	6	6	6	6	6
Flow, litres/s	7.7	8.0	8.7	9.4	10.1	11.2	16.9
Evaporator tube velocity, m/s	0.93	0.97	1.05	1.13	1.22	1.34	2.04
Pressure drop, kPa	10.1	10.88	12.54	14.34	16.30	19.52	41.15
Condenser Fluid	FW	FW	FW	FW	FW	FW	FW
ARI 560 FF	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440	0.0440
Entering temp, C	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Leaving temp, C	33.3	33.4	33.6	33.9	34.2	34.6	36.9
Flow, l/s	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Condenser tube velocity, m/s	2.50	2.50	2.50	2.50	2.50	2.50	2.50
Pressure drop, kPa	70.43	70.42	70.39	70.37	70.34	70.29	70.07
Generator							
ARI 560 FF	0.04403						
Entering temp, C	90.0	91.0	93.0	95.0	97.0	100.0	115.0
Leaving temp, C	85.8	86.6	88.3	90.0	91.7	94.2	106.3
Flow, l/s	13.9	13.9	13.9	13.9	13.9	13.9	13.9
Generator tube velocity, m/s	2.42	2.42	2.42	2.42	2.42	2.42	2.42
Pressure drop, kPa	42.61	42.55	42.45	42.42	42.25	42.11	41.47
Total electric power, kW	3.8	3.8	3.8	3.8	3.8	3.8	3.8
Heat Energy input, kW	244	255.6	273.0	290	307.9	337	505.5
COP	0.66	0.66	0.668	0.678	0.687	0.69	0.70

Table E.1: Absorption chiller's performance for varying hot-water inlet temperatures at the site

Unit size	16JB012	16JB012	16JB012	16JB012
Evaporator pass	2	2	2	2
Generator pass	2	2	2	2
Volts (50 Hertz)	400	400	400	400
Cooling, kW	266.9	231.1	196.8	164.0
Evaporator Fluid	FW	FW	FW	FW
Entering Temp, C	11	11	11	11
Leaving temp, C	6	6	6	6
Flow, litres/s	12.7	11.0	9.4	7.8
Evaporator tube velocity, m/s	1.53	1.33	1.13	0.94
Pressure drop, kPa	24.75	19.12	14.34	10.37
Condenser Fluid	FW	FW	FW	FW
ARI 560 FF	0.0440	0.0440	0.0440	0.0440
Entering temp, C	26.0	28.0	30.0	32.0
Leaving temp, C	31.1	32.5	33.9	35.4
Flow, litres/s	30.0	30.0	30.0	30.0
Condenser tube velocity, m/s	2.50	2.50	2.50	2.50
Pressure drop, kPa	71.35	70.80	70.37	69.94
Generator				
ARI 560 FF	0.04403	0.04403	0.04403	0.04403
Entering temp, C	95.0	95.0	95.0	95.0
Leaving temp, C	88.7	89.3	90.0	90.6
Flow, litres/s	13.9	13.9	13.9	13.9
Generator tube velocity, m/s	2.42	2.42	2.42	2.42
Pressure drop, kPa	42.40	42.37	42.42	42.34
Total electric power, kW	3.8	3.8	3.8	3.8
Cooling Capacity, kW	265.5	229.9	196.5	163
Heat Energy input, kW	366	331	290	255.6
COP	0.73	0.70	0.68	0.64

Table E.2: Absorption chiller's performances for varying cooling-water inlet temperatures at the site

Model Number (TSA.**)				LC-03
Refrigeration Capacity			USRT	50
Chilled Water System	Temperature		^oC	13 to 18
	Water flow rate		m^3/h	30.2
	Pressure drop		m.W.C.	2.7
	Connection Diameter		inch	2.5
Cooling Water System	Temperature		^oC	29.4 to 35.4
	Water flow rate		m^3/h	60.8
	Pressure drop		m.W.C.	6.8
	Connection Diameter		inch	3
Low temp. Hot Water System	Temperature		^oC	90 to 85
	Water flow rate		m^3/h	42.6
	Pressure drop		m.W.C.	1.8
	Connection Diameter		inch	2.5
	Hot Water Three Way Valve	Pressure Drop	m.W.C	5.0
		Connection Diameter	inch	2.5
Overall Dimensions	Length (L)		mm	2590
	Width (W)		mm	1125
	Height (H)		mm	1880
Weight	Operating Weight		ton	3.1
	Shipping Weight		ton	2.7
	Shipping Method			One section
Space for tube removal			mm	2000

Table E.3: Hot-Water fired Absorption chiller specifications [27].

MODEL - 16JB012	
Cooling Capacity, (kW)	429
Chilled Water	
Flow rate, (L/s)	18.5
Pressure drop, (kPa)	47.9
Cooling Water	
Flow rate, (L/s)	27.7
Pressure drop, (kPa)	60.5
Steam, kg/hr.kW	2.30
kg/hr	988

Table E.4: Carrier absorption chiller specifications.

Appendix F

Integrated CHP and absorption-chiller.

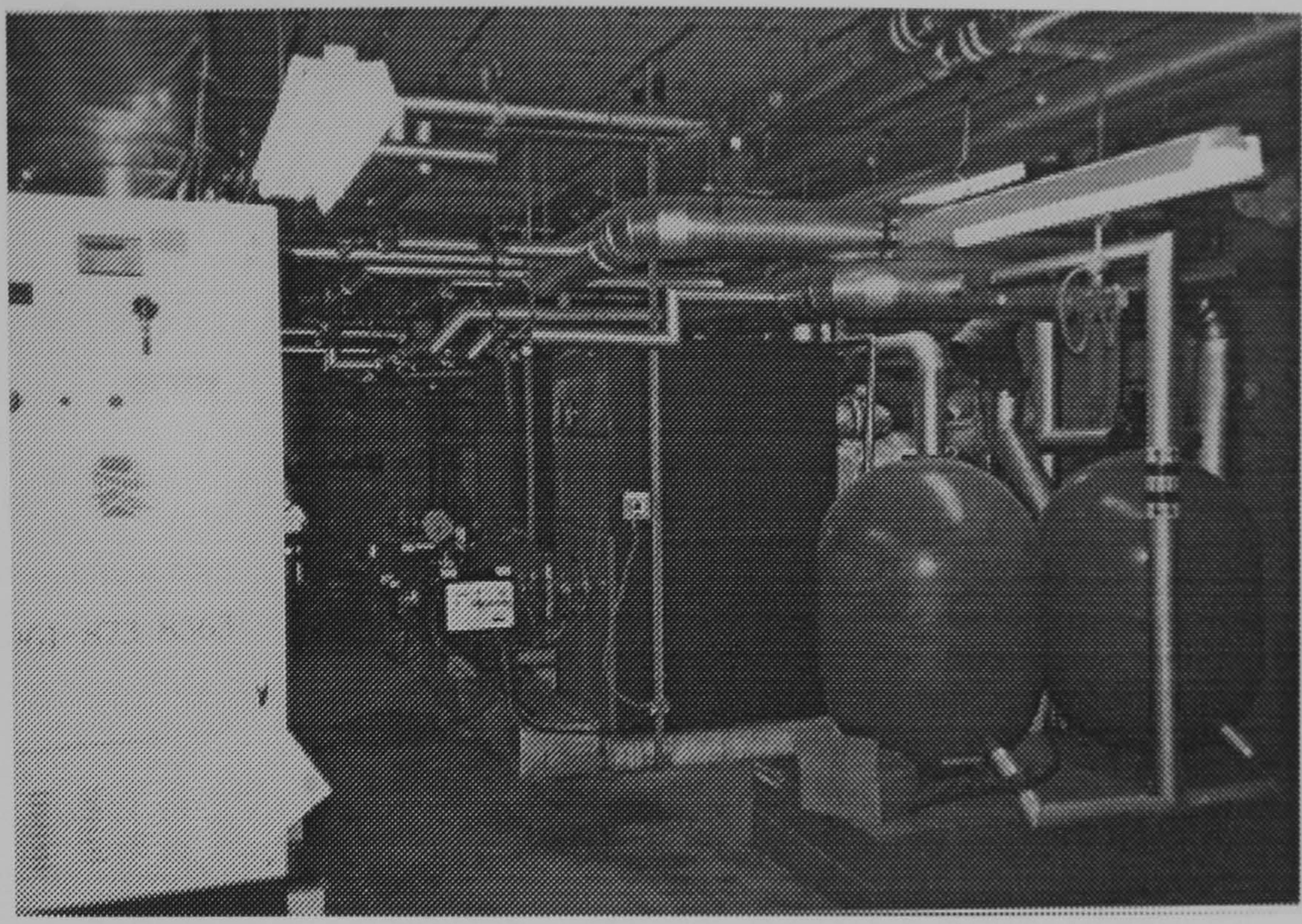

Figure F.1: Photograph of the CHP unit, as installed at the site.

Figure F.2: Photograph of the CHP unit, as installed at the site.